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Components of Spatial Memory: a Developmental Analysis

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Abstract

How is spatial information represented in the developing human brain, and how are different representations combined to solve spatial problems? Neuroscience indicates that mature spatial representations depend on networks of specialised mechanisms that normally interact but are experimentally dissociable. The present studies applied this framework of dissociable components to understanding the development of spatial memory. Two kinds of search task were used. Disoriented adults and 18-24 month olds used conjunctions of colour and room shape to find hidden objects. Three- to six-year-olds searched for toys hidden in an array bordered by landmarks, where the availability of different frames of reference was manipulated by moving subject and / or array before retrieval. Ability to resolve conjunctions of colour and room shape did not depend on language, either in children or in adults, but was mediated by disoriented subjects' erroneous sense of orientation. In small square enclosures, 18-24 month olds were able to use wall colour to reorient. These results argue against previous claims for information encapsulation, but supports the thesis combining different kinds of visual information is difficult in early development. In the array task, core components of adult spatial representation, including parallel egocentric and nonegocentric representations of space, were present as early as three years, and three-year-olds had and greatly favoured representations that were not purely egocentric. Five-year-olds solved viewpoint-independent recall dependent only on local landmarks, showing emergence of an "intrinsic" frame of reference. Distinctive patterns of impairment in use of these frames of reference were found in individuals with Williams Syndrome, and in children born premature or with focal lesions. These patterns, and correlations with other tests, provide evidence that cognitive and neural substrates for spatial memory are dissociable in development, and that children's early spatial errors can be explained by differential rates of maturation for different substrates of spatial representation.

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Published work

A paper describing Experiment 7 (Chapter 4) is in press (Nardini, Burgess, Breckenridge, & Atkinson, in press). Other results from Chapters 2, 3, 4 and 5 have been presented at conferences and published in abstract form (Nardini, Breckenridge, Eastwood *et al.*, 2004; Nardini, 2005; Nardini, Breckenridge, Burgess, & Atkinson, 2005; Nardini, Atkinson, Braddick *et al.*, 2005).

CHAPTER 1

Introduction

1.1 Introduction

Mobile organisms operate within a spatial frame, and benefit from reliable means of revisiting important locations. When a location is not perceptually available, several different sources of information can guide navigation. In humans the visual sense is most strongly allied to spatial tasks, although vestibular and auditory cues are also significant. The questions addressed here are how spatial information is represented in the developing human brain, and how different representations are combined or transformed to solve particular spatial problems.

Spatial representations are those that express directions and distances. To be of use they must include, or be bound to, representations of their targets' identities. This would form the basis for knowing that a slice of cake is on my left, whereas a spider is on my right. The conjunction of angular and identity data is needed to avoid eating the spider, or squashing the cake. The formal requirement for spatial representations – to express both geometric relations and identity information, including visual or semantic properties – is quite complex. Consistent with this, spatial representations in children are reported to undergo a series of errors before reaching the adult state.

To encode a location's direction and distance, two distinct reference systems are available: a location can be referenced internally, with respect to the body, or externally, with respect to objects in the environment. Encodings with respect to the body are subject to error when an organism moves, but would translate straightforwardly into motor actions towards the encoded locations; encodings with respect to external landmarks would provide a basis for accuracy on complex spatial tasks, but not a direct basis for action. In human adults there is evidence for body referenced representations that are updated with movement (**Loomis, Klatzky, Golledge *et al.*, 1993**), body referenced representations that correspond to static viewpoints (**Shelton & McNamara, 1997**) and externally referenced representations that encode locations with respect to environmental features (**Jacobs, Laurance, & Thomas, 1997**). These reference systems closely correspond to those found in other animals, including rats, in which they have been studied in considerable detail (**Gallistel, 1990**); however in developmental studies these different systems have often been poorly distinguished.

The basis for a body referenced spatial coding that is updated during movement would be provided by the continuous addition of the translational and rotational components of own movement to a vector specifying a target's location. This process, *path*

integration, would maintain a representation of a direct route to a nonvisible target. Path integration is the basis for a prodigious homing ability in many insects, most famously the desert ant *Cataglyphis* described by **Wehner & Srinivasan (1981)**. The mechanism is present in mammals (**Mittelstaedt & Mittelstaedt, 1980**), but in the absence of vision mammalian path integration leads to rapid accumulation of error even in nocturnal species, and when landmarks are visible path integration is reset by these (**Etienne, Maurer, & Seguinot, 1996**). In humans the ability to track an invisible object's location whilst moving is also present but inaccurate in the absence of vision (**Loomis *et al.*, 1993**). Information about linear and rotational acceleration and deceleration is available through the vestibular system (**Potegal, 1982**); further displacement cues come from proprioception and efference copy, and accuracy improves when displacement is accompanied by optic flow (**Riecke, van Veen, & Bulthoff, 2002**).

There is evidence for a distinct class of internally referenced spatial representations that are not updated with movement. Humans show a recall advantage from a viewpoint where the original perceptual input is matched (**Shelton & McNamara, 1997**; **Diwadkar & McNamara, 1997**), suggesting that some encoding of the visual percept is preserved. Static representations of this kind are usually described as images or scenes, while representations updated with movement are described as vectors. In human adults, static and updated body referenced representations have been shown to operate simultaneously: the advantage of a matched viewpoint is diminished by an incongruent movement cue, and the disadvantage of a novel viewpoint is reduced when a matching movement cue is available (**Simons & Wang, 1998**; **Wang & Simons, 1999**).

In human adults, static body referenced encodings corresponding to stored visual scenes depend on the ventral visual processing stream (**Ungeleider & Mishkin, 1982**; **Milner & Goodale, 1995**) and parahippocampal cortex, which imaging studies have found active in processing scenes presented from familiar viewpoints (**Epstein & Kanwisher, 1998**; **Epstein, Graham, & Downing, 2003**), and in which an intracranial recording study has found a majority of cells responsive to specific views of landmarks (**Ekstrom, Kahana, Caplan *et al.*, 2003**). In line with other specialised ventral-stream recognition mechanisms, the computational basis for scene recognition can be described as hierarchical correlation detection. That is to say, recognition depends on detecting correlations (and correlations among correlations) which signal the presence of a complex target while showing some invariance to lower-level visual properties such as lighting, size, or exact viewing angle.

By contrast, the localisation of nearby objects with respect to the body depends on the dorsal visual stream (**Ungerleider & Mishkin, 1982, Milner & Goodale, 1995**) and posterior parietal cortex. In primates, posterior parietal neurons encode nearby targets in a variety of body-centred frames of reference, including those centred on the retina and head (**Andersen, Essick, & Siegel, 1985; Duhamel, Bremmer, Ben Hamed, & Graf, 1997**). The activity of some PPC neurons is also modulated by motor demands, consistent with a role is planning movements towards local targets (**Snyder, Batista, & Andersen, 1997**). This network seems to represent an interface between sensory and motor representations, whose computational principle is coordinate transformation, and whose function is to elaborate visual input into representations useful for action.

Representations in the dorsal and ventral streams result from different computations, and express different information. There is evidence that the two systems are dissociable, in patients as well as in healthy controls (**Goodale, Milner, Jakobson, & Carey, 1991; Aglioti, DeSouza, & Goodale, 1995**): dorsal representations are normally recruited preferentially for motor control, particularly where rapid responses are involved. This may be explained by the shorter latencies in the dorsal pathway (**Nowak & Bullier, 1997**), and by the direct projections from posterior parietal to premotor cortex.

A further component of human spatial competence depends on relations between external objects. My keys are on the desk; John's house is between the ice rink and the cemetery. Unlike body referenced spatial representations, representations such as these use frames of reference that are not intrinsic to the speaker. In the simplest case, a cue coincides directly with the target. Here, the cue-target association is sufficient, and no directional or distance information is needed. Direct cues are useful when the target is visible, but navigational targets are often far away or occluded. In such cases, representations with respect to *indirect* cues (distal landmarks) would support flexible navigation. A representation of a target's location with respect to an indirect landmark would necessarily include directional and distance information.

While static and movement-updated internally referenced representations have been likened to mental images and vectors respectively, descriptions of the organisation of externally referenced spatial representations have been contentious. Studies of spatial problem solving by **Tolman (1948)**, **Menzel (1973)**, **Olton (Olton & Samuelson, 1976)** and **Morris (1981)** found in a variety of environments and tasks that mice, chimpanzees, and rats reached nonvisible goals by taking the shortest distances along novel paths. This suggested an internal representation of the environment's layout,

described as a *cognitive map* (**Tolman, 1948**). An organism with such a representation would encode landmarks with respect to a fixed absolute frame of reference and have a record of its own location within the same frame, allowing it to compute a direct route to any represented location.

At the same time, it is always possible to account for indirect landmark use, or wayfinding along novel routes, by spatial computations other than those based on internal maps. A novel route could, in principle, be computed from a set of purely egocentric vectors, although storing a large set of such vectors would entail much more redundancy than would the more parsimonious "internal map". However, some authors do argue that "flexible" navigation is supported by computations based only on body-referenced representations. This view has been put forward most recently by **Wang and Spelke (2002)**. On their account locations are not encoded in extrinsic frameworks except through the medium of language. However there is strong evidence from neurophysiology for map-like representations in mammals, including humans.

O'Keefe and Nadel (1978) have outlined the physiological basis for such representations in the rat hippocampus, where CA1 pyramidal cells fired in response to specific *places* in an environment but were unaffected by facing direction or movement rate. For these "place cells", rotation of visual landmarks caused an equivalent rotation in place fields (the regions in which they fired), suggesting that in the absence of local cues place was determined with respect to indirect landmarks (**O'Keefe, 1978**). Changing environment size (**Muller & Kubie, 1987**) or shape (**O'Keefe & Burgess, 1996**) caused distortions in place field sizes and shapes consistent with a model on which these respond to distal landmark configurations, and not to local features. The functional importance of the hippocampus in rat navigation was confirmed by **Morris, Garrud, Rawlins, & O'Keefe (1982)**, who found in hippocampally lesioned rats a specific deficit in locating nonvisible places with respect to indirect landmarks. The human hippocampus receives input from both dorsal and ventral visual streams, and dorsal stream and hippocampal functions in human spatial processing are normally concentrated in the right hemisphere (**Mountcastle, 1998**). Damage to human right hippocampus was associated with deficits in indirectly but not directly cued retrieval (**Abrahams, Pickering, Polkey, & Morris, 1997**; **King, Burgess, Hartley *et al.*, 2002**), functional imaging has confirmed in healthy humans the implication of right hippocampus in the computation of novel routes (**Maguire, Burgess, Donnett *et al.*, 1998**; **Hartley, Maguire, Spiers, & Burgess, 2003**), and place-dependent firing has been recorded in human hippocampus *via* intracranial electrodes (**Ekstrom *et al.*, 2003**).

Further groups of neurons with specialised properties suitable for wayfinding have also been identified in rodents. "Head direction cells" in the postsubiculum and elsewhere encode heading within the environment, irrespective of place (**Ranck, 1984; Taube, 1998**). It is easy to see how this internal "compass" might complement the hippocampal "map", and algorithms for navigation based on properties of these cells have been proposed (**McNaughton, Knierim, & Wilson, 1995; Becker & Burgess, 2001**). Another significant recent finding has been the identification of neurons in entorhinal cortex termed "grid cells" (**Hafting, Fyhn, Molden *et al.*, 2005**), which make up topographically organised maps based on regular grids of equilateral triangles. These maps are sensitive both to external landmarks and to self-motion, and could provide an interface between self-motion-based path integration and a hippocampal spatial map.

The adult and animal models may not yet provide a settled endpoint for development, but they do offer a framework of separate representational system which developmental studies should address. The most commonly reported immaturity in spatial encoding is "egocentrism": after changing position, young children searched for a stimulus at the position relative to the body that the stimulus previously occupied. On the adult model, mature performance could differ in that static (*e.g.* parahippocampal) representations are not relied on after position change, and/or movement-updated (posterior parietal) representations are accurately updated, and/or locations are encoded with respect to an external reference frame (*e.g.* by the hippocampus), and/or these different representations are correctly integrated.

1.2 Developmental studies of spatial representation

In two classic studies of perspective-taking, **Piaget & Inhelder (1967)** used desktop models of environments to examine children's understanding of viewpoint change. These tasks offered interesting measures of spatial representation, since they required participants to retrieve layouts in a viewpoint-independent manner, which we might now consider to require allocentric (*e.g.* hippocampal) representations. In the "three mountain" task, 4-12 year olds asked to judge what a doll on a different side of the 3D model would see did not dissociate their own perspective from the doll's until 9-10 years. In a "model landscape" task, children were shown locations on a model and asked to find these on the same landscape rotated through 180°. Responses became

more sophisticated with age: at 3-4 years locations were consistent with environmental features but not with places on the model, at 4-5 years locations were determined relative to a single landmark, while at 7 years the full range of landmarks and spatial relations were used. These findings suggested a trajectory for the development of externally referenced representations of location.

On the basis of these and other studies **Piaget & Inhelder (1967)** concluded that young children had a limited understanding of *distance relations* – by which they meant the whole set of laws governing relations between points in space – and a limited ability to understand changes of viewpoint even up to age nine. Follow-up studies criticised aspects of these tasks; for example children performed better on the perspective task when the doll was replaced with a person (**Cox, 1975**; **Fehr, 1979**). A more significant criticism is that children were not engaged within the model environments. Hypothesising a different viewpoint and using cardboard shapes to create a picture of the imagined view, or mapping relations between a model and its 180° equivalent from a viewpoint outside both environments, entailed representations and transformations additional to those required for viewpoint-independent recall. Later studies showed that children asked to imagine being at a different side of a spatial array performed much better given "item questions" (*e.g.* which of four items would be furthest from you if you moved to *x*), than pictorial stimuli (**Newcombe & Huttenlocher, 1992**). All these studies additionally required the suppression of the child's real perspective. This suppression component may have accounted for a large part of children's difficulty with the task. However in these tasks it is not possible to separate failures to represent allocentrically from failures to suppress own perspective.

The most significant developments in the following decades were paradigms developed by **Bremner & Bryant (1977)** and **Acredolo (1978)** based on behavioural measures that placed minimal demands on subjects. Both exploited natural infant behaviours, reaching for hidden toys (Bremner and Bryant), and orienting towards an adult playing "peekaboo" (Acredolo). These techniques offered more direct inferences to spatial representations than could previously be made, and made it possible to assess much younger children. Acredolo and Bremner and Bryant experimentally dissociated *egocentric* and *nonegocentric* responses by moving subjects between presentation and test: following movement a target location was no longer in the same place with respect to the body. Environmental cues, which could serve as landmarks, were additionally manipulated between subjects.

In the **Acredolo (1978)** study, infants sat at a table inside a featureless square enclosure with windows to the left and right. In the training phase they learned to turn

to anticipate the appearance of an experimenter at one of the windows following an auditory cue. In the testing phase they were moved to the opposite side of the table; this translation and 180° rotation reversed the positions of the windows with respect to the body. The auditory cue was repeated and the infant's looking direction recorded. A look to the same side of the body (wrong window) indicated that the experimenter's original location had been learned only egocentrically. Responses were egocentric at 6 and 11 but not at 16 months. When a direct landmark (yellow star) indicated the correct window, egocentrism fell (nonsignificantly) at the intermediate age.

In a follow-up study **Acredolo & Evans (1980)** examined the role of environmental cues, manipulating two factors, salience and coincidence. Flashing (direct) and flashing (indirect) cue conditions were added to the original star and no cue conditions. In the flashing conditions, a window was marked by stripes and flashing lights, a landmark more salient than the star. In the indirect flashing condition the window at which the experimenter did *not* appear was marked. Infants as young as 9 months responded nonegocentrically given a direct flashing direct cue, and those aged 11 months also benefited from the flashing cue when it was indirect. Other studies identified further factors in performance. When a simpler movement, rotation only, was undergone before testing, and when infants moved actively instead of being carried, those as young as 6, 8 or 8.5 months benefited from a direct cue (**Rieser, 1979**; **McKenzie, Day, & Ihsen, 1984**; **Keating, McKenzie, & Day, 1986**).

Direct cues could have provided a basis for nonegocentric response in several ways. The "peekaboo" location could have been associated with the cue, or the additional visual information could have helped infants to track their position as they moved. A serious problem is that direct cues could also have been oriented towards purely because they were visually interesting. In **Acredolo & Evans (1980)** an indirect condition, in which orienting towards the cue would result in error, served as a partial control. Infants orienting towards cues because they were attractive would select the incorrect window more often when it was marked by a cue than when neither window was marked; in fact 11 month olds chose the incorrect window *less* often when it was marked by the indirect cue than when unmarked. Younger infants were incorrect equally often on both conditions. Since those infants' error rates were at ceiling even with no cue, the effect of the indirect cue remains uncertain.

This factor was balanced more carefully by **Bremner & Bryant (1977)** and **Bremner (1978b)**. Nine month olds learned to retrieve a toy hidden in one of two containers on a table in front of them. Either container lids or two halves of the table were painted different colours: both locations were therefore cued, so performance could not be

based on preference for a cue over no cue, and colours and hiding locations were counterbalanced. After five training trials on which a toy was hidden and retrieved at the same container, one of three manipulations occurred: no movement took place, or the child was brought to the opposite side of the table, reversing the container's positions with respect to the body, or the same reversal was effected by rotating the table by 180°. A toy was again hidden in one of the containers and the container searched was recorded.

These infants had considerably more information than Acredolo's: since the final hiding event occurred *after* any movement, a static body referenced representation of the final location would suffice for retrieval in all conditions. The measure was not of the quality of spatial encoding following displacement, but of the interference effect of the five previous trials on the final trial. The results are relevant to the Acredolo paradigm, in which repetition of a single response also preceded a final test trial.

The task was devised to investigate the classic "A not B" error described by **Piaget (1954)**, where children who had repeatedly retrieved an object hidden at location A continued to search A even after seeing it hidden at novel location B. Bremner and Bryant introduced movement conditions to dissociate the hiding place from the location designated by the practiced motor response: response perseveration, suggested by Piaget, predicted repetition of the practiced motor response regardless of the place it indicated, whereas an alternative hypothesis predicted a perseverative response towards the practiced hiding place, regardless of the motor response entailed. Two studies with nine conditions manipulating the factors practice and test location, view change and cue type (**Bremner & Bryant, 1977**; **Bremner, 1978b**) found much evidence for response perseveration but none for place perseveration.

The finding that retrieval was based on a preference for a practiced motor response suggests that the reported egocentrism on the Acredolo task could also have been based on practiced response and not on spatial encoding. Indeed egocentric responses fell from 88% to 38% on the Bremner task when it was not preceded by training trials (**Bremner, 1978a**).

While the Bremner tasks took place in children's own homes, Acredolo's were set in a laboratory, environments varying on at least two factors, familiarity and landmark richness, which **Acredolo (1979)** investigated with a non-repetitive AB task. Nine month olds solved the task in a familiar landmark-rich environment (home), but not in an unfamiliar environment, whether landmark-rich (office) or not (laboratory). This suggested some interesting possibilities about children's spatial representations:

perhaps orientation was more easily maintained in the familiar setting because that environment was more comprehensively encoded – however other possibilities, including better performance in an environment where the child feels relaxed, could not be ruled out.

To solve all these tasks it would be sufficient to update a body referenced representation of the target while moving. However displaced children were usually carried by a parent, so did not experience all displacement cues and need not have attended to their movement. **Acredolo, Adams, & Goodwyn (1984)** reported 62% correct retrieval on an AB task when 12 month olds walked to a new position, compared with 25% when they were carried. Although walking children may have been more attentive and had additional information about their displacement, Acredolo and colleagues reported that the most significant reason for success in walking children was that they were more likely to *fixate* the target as they moved.

Fixation was possible in all these studies, since the room remained lit and gaze direction was not controlled. Tracking a feature that directly indicates a hidden object's location, such as a container or a window, would involve localising it within the 2D frame of the retina and using eye and head movements to keep it in the fovea during displacement. Visually fixating the hiding place would keep it perceptually available between presentation and test, setting the retrieval interval to zero and producing a task that no longer meets the criterion for a test of encoding. In most of the studies described it is unknown how many infants used the strategy - high rates of error in young infants suggest that they did not track hiding places, however we cannot be sure whether older infants had learned to encode, or whether they had learned to track.

It is now thought that the additional requirement to inhibit practiced motor responses, common to these tasks, depends on prefrontal cortex (PFC). Lesions of PFC in adult rhesus monkeys impair AB performance, while in adult humans performance on a variety of delayed visuomotor tasks is PFC dependent; maturation of PFC may therefore be necessary for the production of novel motor responses on the AB task **(Goldman-Rakic, 1987; Diamond, 1988; Damasio & Anderson, 1994)**. In very young infants motor responses and spatial representations may be dissociated; mathematical models of developing interactions between perception, representation, and action have been developed, for example by **Thelen, Schoner, Scheier, & Smith (2001)** who gave a specific account of infants' perseverative reaching errors. AB reaching studies continue to be conducted, but primarily to investigate the perseverative aspect of the task.

Since these early studies one approach has been to assess spatial encoding purely on the basis of observation, recording responses that did not need to be learnt and were not reinforced; these methods employed considerable ingenuity to make inferences about infants' encodings. **Baillargeon & Graber (1988)** examined understanding of A and B locations at 7-8 months with an entirely passive procedure in which infants watched different events occurring. The dependent measure was looking time, a significant difference between looking times for two events indicating that the perception of these differed. Children saw a toy hidden at one of two locations and retrieved 15 seconds later from the same place ("possible event"), or from the other place ("impossible event"). A longer mean looking time for the impossible event was recorded at 8 months, though not at 7 months. Since these events differed only in the relative places of hiding and retrieval, 8 month olds must have been sensitive to this information. It will be recalled that 9 month olds made the A not B error on a reaching version of a similar task. The suggested dissociation between reaching and looking responses was confirmed by **Diamond (1990b)** who compared looking and reaching measures on an AB task at 8 and 13 months and found better performance on the looking measure. Increased looking times have also been recorded at earlier ages than correct searches in other within-task comparisons, *e.g.* in an invisible displacement paradigm (**Hood, Cole-Davies, & Dias, 2003**).

A related procedure was used by **Kaufman & Needham (1999)** to evaluate infants' spatial encoding following viewpoint changes. Visual dishabituation is another passive method for assessing sensitivity to a difference between two stimuli. The subject views one stimulus during the habituation phase. In the test phase, increased looking at a novel stimulus that differs in some respect provides evidence for a sensitivity to the difference. In this experiment 6.5 month olds habituated to a toy in a constant position on a table. They then either remained at the accustomed viewing position or moved to a novel position at the opposite side of the table, while the toy remained still or moved. When both toy and infant moved, the toy occupied a novel position on the table but the same position relative to the infant.

Regardless of viewing position, infants looked longer (dishabituated) when the toy's position on the table changed, but did not dishabituate when the toy's position remained constant. A static or non-updated body referenced representation of the toy's position would predict dishabituation when infants moved but the toy did not since this changed the toy's position in relation to them, and no dishabituation when both infant and toy moved since this manipulation kept the toy's relative position constant. The opposite pattern of results was obtained, demonstrating a response to a

change in the toy's position within the space of the table top, but not to a change in its egocentric position relative to the infant. Therefore on a task that did not entail a potentially perseverative motor response, infants as young as 6.5 months showed awareness of an object's position in an extrinsic spatial frame, as distinct from an egocentric one.

The argument for a nonegocentric awareness of location is good because there is no simpler perceptual explanation for the difference. Crucially, whether a longer looking time really signifies detection of a novel stimulus or not (**Sirois & Mareschal, 2002**), looking-time responses of infants in this study were to displacements within the table, not displacements with respect to themselves. A question remains about what kind of representations might underlie such a sensitivity at this young age. It could be provided either by an externally referenced representation that states the toy's location within the framework of the table top and surrounding landmarks. It could also be provided by an internally referenced representation that states the toy's location with respect to the infant, and is updated as the infant is moved around the table.

A different set of studies asked older children to find hidden objects in environments that presented wider ranges of hiding locations and manipulated cues in more complex ways. Children did not normally change position between presentation and test, so static body referenced encodings would have sufficed, but these studies investigated which environmental cues children would additionally exploit to find hidden objects.

With nine search locations in a vertical 3x3 array, **Blair, Perlmutter, & Myers (1978)** found better retrieval at 3.75 than at 2.25 years, better performance at both ages when each location had a distinctive picture cue, and best performance when these were verbally labelled by the experimenter. Both age groups also searched the location correct on the preceding trial at rates above chance, an error similar to the A not B. **Horn & Myers (1978)** reported that picture cues on containers improved performance at 3 but not at 2 years, and that when container positions were changed, 3 year olds used the cues to locate the object while 2 year olds searched by position. When the picture cues were not arbitrary but depicted the hidden objects, 2 year olds benefited from the cues (**Ratner & Myers, 1980**).

DeLoache & Brown (1979) hid a toy in natural locations, such as behind a door or under a cushion, in 18–30 month olds' homes. Children as young as 18 months retrieved the toy after long delays, even overnight. These natural locations were recalled strikingly better by this age group than the experimental containers used in

other tasks. In a follow-up with 22-29 month olds, **DeLoache & Brown (1983)** compared within subjects the "natural locations" retrieval task with one in which hiding locations were boxes identical except for attached picture cues. Retrieval from boxes was significantly worse than from natural locations. The authors suggested that with boxes the relations between picture cues and locations were arbitrary, whereas with natural objects "information about the hiding place is intrinsic to the place itself". In fact besides intrinsicness or familiarity, hiding locations for varied on at least two further factors - discriminability and proximity to each other - so no clear conclusion can be drawn.

A second experiment eliminated one of these differences, spacing hiding locations approximately equally for the two tasks, and compared retrieval from natural locations with retrieval from boxes which this time were indistinguishable (uncued), but arranged either adjacent to a natural cue such as an item of furniture, or not. When boxes were not adjacent to cues, retrieval was worse than from natural locations. When boxes were adjacent to cues, 18-22 month olds did not improve, but 24-29 month olds performed better than without cues, and as well as with natural locations.

This last result is often cited because it represents an early measure of children's ability to locate an object relative to a direct landmark. However since each cue corresponded only to one container, the associations between these and the containers need not have been spatial. It also remains uncertain whether natural locations were superior to picture cues because they were larger, because experience had made them more memorable, or because experience had made representations of their spatial layout more comprehensive.

These studies were informative about children's abilities to remember associations between hiding places and hidden objects, but not about specifically spatial representations involving directions or distances. We can draw some conclusions relevant to any test based on hidden objects: even direct cues vary greatly in their usefulness to searching infants; performance is influenced by the familiarity of the cue, the nature of its association with the hidden object, and the way in which the experimenter draws attention to it. These factors can similarly be expected to matter in the case of indirect cues.

The direct cue studies described must because of their settings have included many uncontrolled indirect cues. However it seems likely that where direct cues existed, or an encoding with respect to the self was sufficient, the effect of indirect cues on performance was small. Their influence can be assessed by precluding one or both of

these easier encoding strategies, or by manipulating the availability of indirect cues between conditions.

In a circular environment with eight identical hiding places and no direct cues, **Mangan, Franklin, Tignor et al (1994)** reported that children aged below 24 months could not locate a hidden toy, whereas those above 24 months could. Indirect cues such as trees and buildings were visible beyond the test area's perimeter, and the older children may have profited from these. However the older children's superior performance could likewise have represented an improvement in accurately localising the hidden objects with respect to themselves, or in remembering the place's position within the array of hiding places.

Also in a circular environment but with no external cues, **Bushnell, McKenzie, Lawrence, & Connell (1995)** asked 12 month olds to search for a toy hidden under one of 58 overlapping cushions, a subset of which could be distinctive in colour and so serve as cues. Toys were hidden beneath an uncued cushion (no cue), a distinctive cushion (direct cue), a cushion adjacent to a single distinctive cushion (indirect cue) or a cushion between two distinctive cushions (two indirect cues). Subjects were not repositioned between hiding event and search, although fixation was interrupted, so a body referenced representation was sufficient for retrieval, but the different conditions assessed the additional benefits of direct and indirect cues.

In a first experiment search was highly successful with a direct cue, and less successful with an indirect cue, but as there was no uncued condition it is not known whether indirect cue performance represented any improvement over an uncued baseline. A second experiment compared indirect and no cue conditions, and found significantly *lower* retrieval rates with an indirect cue than with no cue. The authors suggested that indirect cue coding is more complex than either no cue or direct cue, and that perhaps these strategies were confounded. The confound is not easily explained, because errors in the indirect condition did not consist of searches *at* the indirect cue: search was inaccurate but still centred around the correct cushion. These are interesting results, and it is a pity that this task was not repeated with older children – at 12 months the children in this study were much younger than those in DeLoache and Brown's.

It is possible to disagree on the descriptions of these environments in terms of direct and indirect cues. First, "uncued" hiding locations were often identical containers or cushions; it would be more accurate to say that these locations were directly cued, but that the cues were indistinguishable. When choosing among several identical cues

which match the hiding place, a response to the nearest matching cue would have to be inhibited; evidence that response inhibition depends on an additional cortical mechanism has already been briefly reviewed. Second, it has already been noted that since any visual feature of a testing room is a potential cue, many experiments included a large number of indirect cues. Even in the sparse environment achieved by Bushnell *et al.*, the boundary of the test area represented an indirect cue, and locations could have been encoded with respect to the arena's edge. Studies by **Huttenlocher, Newcombe, & Sandberg (1994)** and **Newcombe, Huttenlocher, Bullock Drummey, & Wiley (1998)**, in which 16-24 month olds retrieved buried toys from a sandbox, are pertinent to both these observations. Toys were concealed in the sand and not directly cued by identical containers, but the authors recognised the potential of the edges of the box to serve as indirect cues.

Seated opposite a 152cm x 41cm sandbox, children watched as a toy was buried at locations along the box's length. Following a break in fixation they searched for the toy. In the 1994 study, systematic biases provided evidence for encodings with respect to the edges of the box at 16-24 months. In the 1998 study, 16 to 36 month olds searched after walking to the opposite side, a manipulation that precluded use of those egocentric representations not updated with self-motion. Additional visual cues in the testing room were either visible, or hidden by a screen. All age groups searched accurately from the opposite side, and after age 22 months performance improved when the additional room cues were visible, a result consistent with accurate updating with movement ("dead reckoning") in younger children, and an emergence of allocentric encoding with respect to distal landmarks at 22 months. A question remains about the additional role of cues provided by the shape of the box, which were identified in the 1994 study. Representations of toys' places within a frame of reference defined by the box would provide a strong basis for retrieving them from the other side, additional to any provided by dead reckoning or room landmarks. However it was not possible to distinguish between these kinds of encoding in this study.

A further result from the **Newcombe *et al.* (1998)** analysis was that children who walked to a new position were less accurate than those in the previous study who had remained in the same place, consistent with an advantage for representations made available by an egocentric frame of reference. The view-change condition however entailed an additional walking task, which children who answered from the same place did not have to do. It is probable that keeping the target consistent with the body – and therefore with egocentric representations such as stored visual scenes – produced recall advantages. However the magnitude of the difference cannot be

interpreted as a direct indicator of this spatial factor, since we do not know how large a part of it is attributable to an interference effect from the walking task.

In a further follow-up with the sandbox apparatus, **Sluzenski, Newcombe, & Satlow (2004)** tested 18-, 24-, 36-, and 42-month-olds with three extensions of the original task; memory for multiple locations in the box, use of one object as a landmark to find another, and memory for a single location after an extended (2 minute) delay. They asked whether the timing of the transition to use of room landmarks they previously reported – around 22 months – would be matched by changes on these related spatial tasks. As predicted, on all tasks the most dramatic changes occurred over the 18-24 month interval.

The authors argue that this rapid period of development in spatial memory could depend on a common neurodevelopmental change, and suggest hippocampal development in particular. The argument for a common basis would be strengthened by within-subjects comparisons of the various tasks. The authors also do not demonstrate any specificity to the spatial domain – 18-24 months could be a critical period in general– but in any case their evidence that it is a critical period for spatial tasks (at least) is good. In particular, they identify a qualitative change from random to nonrandom searching for a second hidden object, and a transition from failing to understand to completing a landmark task.

A criticism common to many of these studies is that cues were not adequately distinguished or controlled. Specifically spatial factors in performance were impossible to extract (**DeLoache & Brown, 1983**), or differences between conditions were too many for performance differences to be attributed to the effect of a single type of cue (**Newcombe et al, 1998**). A parallel literature has used tasks and environments that are much more carefully controlled. Rodent spatial tasks are characterised by sparse environments and strict cue control. Some also depend on aversive stimuli rather than rewards, and require large numbers of trials. They have been highly successful in separating the different components of spatial representations, including path integration (**Etienne *et al.*, 1996**) and indirect landmark use (**Morris, 1981**). Could design elements of these tasks be adapted for developmental studies?

One reason why developmental studies have typically had poor cue control is undoubtedly that it is more difficult to build highly controlled environments on a human scale than on a rodent scale. This is a practical problem, which can be overcome, whereas aversive stimuli and large numbers of trials cannot be used as a

matter of principle. However these elements of rodent studies may not be essential. Search-task equivalents of aversive paradigms are available, and humans are usually much quicker than animals to learn tasks and do not need extended training and testing. It should therefore be possible to adapt animal spatial paradigms for children, and a small number of developmental studies have adopted this approach. This represents a recent trend, although the procedures on which these studies are based have been established for some time. Two rodent tasks recently adapted for children are the Morris water maze and the Cheng reorientation paradigm.

In the task devised by **Morris (1981)** rats swimming in a round enclosure learned to find a nonvisible platform below the water's surface, which was indirectly cued by objects external to the enclosure. Rats placed at a novel point of entry (POE) headed directly for the platform, a behaviour said to be based on an allocentric representation of the layout of indirect cues. Ability to find the hidden platform in young rats was reported to follow the neuroanatomical maturation of the hippocampus (**Rudy, Stadler-Morris, & Albert, 1987**), and was lost following hippocampal lesion (**Morris et al, 1982**). This implicates a structure associated elsewhere with indirect landmark use. Rodents have also been tested in "dry" water mazes, where the task is not aversive (escape from water), but appetitive (finding buried food). These environments are more suited to be adapted for children. "Dry" and "wet" water maze tasks are broadly comparable, although it has been reported that rats use landmarks less effectively in appetitive Morris tasks if they are disoriented (**Gibson, Shettleworth, & McDonald, 2001**; **Golob & Taube, 2002**).

Whether subjects tested from a novel POE are disoriented (to eliminate path integration) or not, the use of the novel POE always precludes use of static body referenced representations. In this respect an adaptation of the Morris task by **Overman, Pate, Moore, & Peuster (1996)** represented an improvement in cue control over the **Mangan et al (1994)** and **Bushnell et al (1995)** circular environment search tasks. Children aged 3-12 years searched for an object hidden under plastic chips in a 3.6m wide "pool" surrounded by a curtain with 8 picture cues. Performance, measured by distance travelled to target from a novel POE, improved with age up to 6 years where it reached ceiling. The authors concluded that "spatial relational solutions are not fully mature until approximately 6 years". However their finding that performance *improved* when the picture cues were removed precludes any significant role for indirect cues, and it seems more likely that the task was solved by path integration.

In a second adaptation of the Morris task, **Overman et al (1996)** asked 3-13 year olds and adults to search for a small object in an outdoor circle 60m wide amid visible distal cues such as buildings and trees. Before searching subjects were driven blindfolded circuitously in a golf cart, which placed them, disoriented, at a novel POE. Performance improved between 3 and 10 years, when it reached the adult level. Adults and 10-13 year olds took almost direct paths to the target, while 3-5 year old paths were on average 3 times the length of a direct path. Successful disorientation would have eliminated the path integration cue, making this a pure test of indirect landmark learning, but results from a blindfolded pointing measure showed orientations consistently better than chance. The authors' intention in blindfolding and driving circuitously was actually not to disorient, but only to prevent subjects from retracing the path they had just followed, however full disorientation would have been better.

Lehnung, Leplow, Friege *et al.* (1998) tested 5, 7 and 10 year olds in another Morris-inspired enclosure 3.6m wide with distal cues (four pictures on surrounding curtain) as well as proximal cues (two toys on the floor). The search task, adapted from the Radial Arm Maze (**Olton & Samuelson, 1976**), was to find previously presented lights on the floor without revisiting lights. Cue and subject positions were manipulated so that search was either from novel POE with proximal cues; same POE with proximal cues rotated; same POE with proximal cues removed; or novel POE with proximal cues removed. On novel POE trials children were rotated several times with eyes closed, though it is uncertain whether this was sufficient to induce disorientation and so eliminate solutions based on path integration.

When proximal cues rotated, 5 year olds but not 10 year olds searched according to the rotated cues. When these were removed, 10 year olds but not 5 year olds searched correctly. These results are consistent with use of the distal cues at 10 but not at 5 years. Novel POE conditions were little different to their same POE equivalents at all ages, a result consistent with either cue use or, provided that disorientation was not effective, path integration. However the use of rotated proximal cues, which would have conflicted with any path integration information that was available, shows that whether path integration was available or not, the effect of proximal cues was stronger for younger children.

Using a similar procedure with a wider range of ages, **Leplow, Lehnung, Pohl *et al.* (2003)** found that children as young as 3 years made few errors finding proximally cued places from a novel POE. When these proximal cues were rotated to conflict with distal cues, children aged 3-7 searched incorrectly, whereas 10-12 year olds did

not. In a separate sample, rotating the distal cues themselves was confirmed to diminish performance at 11 years but not at 5 years. These studies represent a successful adaptation of a combination of rodent spatial tasks, using a carefully designed environment in which intramaze and extramaze cues were completely controlled.

Results from both studies indicate that use of proximal (*i.e.* immediately adjacent) cues emerges much earlier than the use of distal cues. This is not surprising since use of proximal cues does not depend on directional or distance coding. It is sufficient to recognise and approach the cue. Use of distal cues emerged quite late, between 7 and 10 years. These could have served to indirectly code the hidden locations, for example on an allocentric "map", as well as to maintain orientation and so calibrate representations based on heading and path integration. These studies show evidence for a change in spatial coding between 7 and 10 years. The authors suggest that the change of strategy could depend on accelerated neurogenesis in prefrontal cortex, reported between 7 and 12 years (**Huttenlocher, 1994**). Prefrontal cortex could be involved in the more general problem of resolving cue conflicts, in this case inhibiting a response towards the dominant proximal cues when these conflict with distal cues.

It should be asked how the 7-10 year transition for distal landmark use reported by **Leplow *et al.* (2003)** relates to the much earlier 18-24 month transition reported for use of distal landmarks (**Newcombe *et al.*, 1998**), and near landmarks (**Sluzenski *et al.*, 2004**) on another search task. The outcome of the 18-24 month old transition was an ability to benefit from landmarks at all, whereas the outcome of the 7-10 year transition was an ability to select these even when they conflicted with other landmarks and with path integration. The authors of these studies suggested that these transitions depend on different neurodevelopmental changes: in the hippocampus at 18-24 months, and prefrontal cortex at 7-10 years. There is evidence for accelerated development of both structures at the times suggested, but there is of course a great deal of other development happening at the same time. Indirect links such as these between neural development and behaviour provide suggestive hypotheses that should be tested with clinical groups or neuroimaging techniques.

An adaptation of a different rodent paradigm has been successful in inducing disorientation and so forcing a search based on external cues. **Hermer & Spelke (1994; 1996)** adapted for children and adults a rat task devised by **Cheng (1986)** set in a rectangular enclosure with two long walls and two short walls, and all external cues excluded. When no other features are provided, the room's shape gives disoriented subjects a partial cue to orientation, which remains ambiguous because the enclosure

appears the same through 180° rotation. In such an environment disoriented rats searched according to this "geometric" cue, and interestingly continued to search only using geometry when distinctive colours and odours marked each corner, even though rats commonly associate such cues with rewards in other settings (**Cheng, 1986**; **Gallistel, 1990**). Recreating the environment on a human scale, **Hermer & Spelke (1994; 1996)** reported a similar result in disoriented 18-24 month olds, who ignored the cue provided by a single blue wall and searched only according to enclosure geometry. Subsequent studies have confirmed the result but found that it does not hold in larger enclosures, or with solid (furniture) cues (**Learmonth, Newcombe, & Huttenlocher, 2001**; **Learmonth, Nadel, & Newcombe, 2002**). Perhaps these manipulations abolish the effect because larger distal cues (wall colour in the large room) or cues that are solid objects (furniture) are liable to be more reliable, and are therefore processed differently to the coloured wall in the small enclosure.

The distinctive characteristic of the Hermer and Spelke studies in the present overview is that they represent an unprecedentedly high level of cue control, wholly specifying environmental cues with a carefully constructed enclosure, and internal cues with an effective disorientation procedure. Although isolating a single cue or process is not the only means of assessing its contribution, the fact that only one set of studies among all those reviewed might have succeeded in doing so is remarkable. Many studies compared conditions on which more than one cue was available, which would be acceptable were it not for the presence of other confounds between conditions. Few sought to test hypotheses based on adult and animal findings, which are more detailed than those in the developmental literature.

Further possibilities for process specific investigations of spatial encoding in children come from clinical populations. The adult physiological model sketched briefly in the introduction suggests a number of relevant dissociations, including hippocampal *vs.* parahippocampal regions, dorsal *vs.* ventral visual processing streams, right *vs.* left hemispheres; these represent decreasing levels of precision for making process-specific distinctions.

Comprehensive visuospatial assessments of children with early focal cortical injury have been carried out by Stiles and colleagues (**Stiles-Davis, Sugarman, & Nass, 1985**; **Stiles, Stern, Trauner, & Nass, 1996**; **Stiles, Bates, Thal *et al.*, 2002**), using tasks involving spatial grouping, block construction copying, and drawing, and basing analysis on comparisons between left and right hemisphere damaged children. Right hemisphere damage was associated with impairments in forming spatial groupings, producing well configured copies of block constructions, and drawing well integrated

pictures. Although most of these patients showed remarkable recovery compared with those obtaining similar injuries in adulthood, fine grained analysis has shown persistent deficits, and suggested that apparently normal performance is sometimes based on alternative strategies which have been developed to compensate for deficits (**Stiles, 2000**).

These manipulating, constructing and drawing measures involved a multitude of perception and performance demands, and were many levels removed even from those developmental spatial encoding tasks which have already been described as not process specific enough. At the same time, collapsing all focal lesions according to a hemispheric distinction reduced the physiological data to the most rudimentary level of description. These interesting data, which represent the most comprehensive account of spatial ability in children following cortical injury, therefore do not provide us with many insights into the neural basis for different components of spatial representation.

Other insights may come from clinical populations who have not sustained injury, but have a developmental disorder leading to distinctive cognitive deficits. A genetic disorder relevant to investigations of spatial cognition is Williams Syndrome (WS), which is caused by a deletion on chromosome 7 (**Ewart, Morris, Atkinson *et al.*, 1993**) and has an estimated prevalence of 1 in 7,500 (**Stromme, Bjornstad, & Ramstad, 2002**). WS is associated with an unusual cognitive profile, with great impairment on a range of visuospatial tasks (**Bellugi, Sabo, & Vaid, 1988**) contrasting with relatively fluent language. Within the visuospatial domain, impairments are greatest on construction tasks (**Braddick & Atkinson, 1995, Atkinson, Anker, Braddick *et al.*, 2001**), while face and object recognition are relatively spared (**Tager-Flusberg, Plesa-Skwerer, Faja, & Joseph, 2003; Wang, Doherty, Rourke, & Bellugi, 1995**). Compared with mental-age matched controls, memory for visual patterns is typical whereas memory for spatial sequences is impaired (**Vicari, Bellucci, & Carlesimo, 2005**).

This cognitive profile may correspond to a dorsal-ventral dissociation, and results from a range of tasks suggest that visuospatial deficits in WS are concentrated in tasks thought to depend on the dorsal visual stream (**Atkinson, King, Braddick *et al.*, 1997; Atkinson, Braddick, Anker *et al.*, 2003; Paul, Stiles, Passarotti *et al.*, 2002**). Structural imaging indicates that the WS cognitive profile is paralleled by abnormal brain organisation, including a volume reduction in primary visual cortex and unusual organisation of the frontal lobes (**Reiss, Eckert, Rose *et al.*, 2004a**), and abnormally low hippocampal activation on PET and MRI (**Meyer-Lindenberg, Mervis, Sarpal**

et al., **2005**). Consistent with the hypothesis of a dorsal-stream deficit based on behaviour (**Atkinson *et al.*, 2003**), there is evidence from functional imaging that deficits in WS can be localised in the posterior parietal cortex (**Meyer-Lindenberg, Kohn, Mervis *et al.*, 2004**). Detailed studies to dissociate representations in spatial memory in WS have not yet been undertaken, and this group would be an interesting test case for the hypothesised neural bases of different spatial representations. It should be noted that developmental disorders differ from injuries acquired in adulthood in that the developmental process itself may be affected, leading to an atypical outcome (**Karmiloff-Smith, 1998**). Therefore even if a discrete initial impairment can be identified, the outcome of development may be anomalous in other ways.

1.3 Conclusions

Spatial representations represent the basic components of spatial competence. Ample evidence from animal and adult studies shows that spatial behaviour depends on a range of different representations, which normally operate in parallel but can be dissociated. Evidence from neuroscience further indicates separate neural bases for these. Classic developmental studies described behavioural aspects of young children's orientation in space, and went some way towards identifying the most important cues and strategies at young ages. The majority did not have a special concern with *representations*, but studied spatial competence in a more general sense.

More recent studies have adopted elements of animal spatial tasks, whose design has traditionally been more rigorous. Minimal environments with carefully controlled cues make it possible to attribute differences between conditions directly to spatial factors. Authors have shown that such environments can indeed be used with children, and yield interesting results (*e.g.* **Lehnung *et al.*, 1998; Hermer & Spelke, 1994**). These studies have also begun to make meaningful connections with models and predictions from the adult and animal literature.

Developmental studies should aim to assess independently those spatial representations elsewhere shown to be neurally or behaviourally dissociated. This approach would enable different models of development to be assessed. Most intuitively appealing is the thesis that immaturities result from differences in the developmental trajectories of different representations, where some are slower to develop than others. One finding consistent across the developmental literature is that

reference frames based on the body are the earliest to be used, and those based on the environment the last.

Dissociating different representations and tracing developmental trajectories for these would be a powerful approach, subject to an important issue of interpretation. Behavioural responses cannot be relied on to show evidence for all representations that are present, but will only show evidence for those representations that have been selected for action. Although selection processes – which could involve higher-order selection mechanisms and/or direct interactions (*e.g.* inhibition) between different representations, may be difficult to discern in behavioural paradigms, they must also be considered a part of "spatial representation". It should be acknowledged that those representations that are detected behaviourally may be a restricted subset of an organism's neural encodings of space, the rest being undetectable behaviourally because they have been inhibited or not selected for action.

CHAPTER 2

Adults' reorientation using geometry and colour

2.1 Introduction

To extract features in the environment rapidly, human perception relies on highly specialised mechanisms. Visual functions depend on different regions of cortex, and focal damage results in specific visuocognitive impairments. At the same time, flexible behaviour depends on combining representations of many kinds. Yet integrating representations from different perceptual domains, the binding problem (Rosenblatt, 1961, von der Malsburg, 1999) grows more difficult as representations become more specialised. Specialisation on the one hand, and flexible combination on the other, are therefore two adaptive design principles whose requirements are in opposition.

On Fodor's (1983) influential account of the trade-off, many perceptual processes are so rapid, automatic, and domain-specific, that they are informationally encapsulated and "cognitively impenetrable". The difficult questions are what kinds of perceptual representations can be shared, and how. The studies in this chapter take as their starting point an interesting reported failure to combine visual information in a spatial task. In a rectangular enclosure with a single brightly coloured wall, disoriented rats and human children searching for a hidden object disregard the colour cue and take their bearings only from the enclosure's shape (Cheng, 1986, Margules & Gallistel, 1988, Hermer & Spelke, 1994, 1996, Wang, Hermer, & Spelke, 1999).

When no colour cue is present, the enclosure looks the same under 180° rotation (Figure 1 a). Subjects who do not know which way they are facing because they have been disoriented by turning on the spot with eyes closed would, at best, divide their searches between the correct corner and its rotational equivalent. Hermer & Spelke (1994, 1996) found that 18-24 month old children showed this pattern, so demonstrating early sensitivity to the "geometric" cue provided by the enclosure's shape. Surprisingly, when a disambiguating colour cue was added (Figure 1 b), 18-24 month olds still searched using only enclosure geometry. The result suggests specifically a problem with combining the two kinds of visual information, since control conditions showed participants able to use a colour cue when it *directly* indicated the hidden object.

This result has been influential because, on the interpretation of Spelke and colleagues, it supports the thesis that cognitive development depends on Fodorian "modules", which are innately specified and task specific. The disregard of colour in the disorientation task is explained by a task specific "geometric module", whose

operation is only revealed under disorientation, and which is informationally encapsulated in that it is impenetrable to colour information (Hermer & Spelke, 1994; 1996).

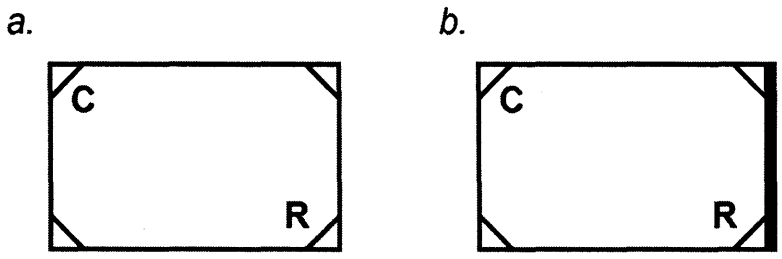


Figure 1. *Testing enclosures used by Hermer & Spelke (1994, 1996)* ***(a)*** *The correct corner C was visually indistinguishable from its rotational equivalent R.* ***(b)*** *A single brightly coloured wall resolved the ambiguity, but 18-24 month old children ignored this colour cue, and still confused locations C and R.*

Hermer and Spelke's results are interesting because so counterintuitive, but their importance as evidence for the "informational encapsulation" predicted by the modularity thesis can be overstated. If the modularity thesis is correct, examples of failures to share information across cognitive domains should be common. They may well be: visual illusions are not extinguished by knowledge about the stimulus; procedural knowledge of a motor task can fail to translate into explicit knowledge. Furthermore, the "blue wall" result is weak evidence for "informational encapsulation" as it includes no measure of whether the colour information has been taken in at all, on the same trials on which it subsequently failed to be used. (Evidence that colour can be used comes from a separate control condition which takes a slightly different form).

The most intriguing aspect of the reorientation failure is that it is seen in young children but not in adults. This suggests that, as far as the visuospatial cues provided by colour and geometry are concerned, children are more "encapsulated" than adults. Some developmental change must make it possible to combine representations more flexibly in adulthood. Spelke argues that the transition to success depends on the acquisition of spatial language, which can combine colour and shape terms. Evidence comes from correlational studies of children's vocabularies (Hermer-Vazquez, Moffet, & Munkholm, 2001), and child-like disregard of colour in adults when they perform a concurrent verbal task (Hermer-Vazquez, Spelke, & Katsnelson, 1999). Recent studies suggest that the language account cannot be right, since pigeons

(Kelly, Spetch, & Heth, 1998), fish (Sovrano, Bisazza, & Vallortigara, 2002), and rhesus monkeys (Gouteux, Thinus-Blanc, & Vauclair, 2001) can solve the task. The task is also solved at younger ages when the enclosure is made larger (Learmonth *et al.*, 2001, Learmonth *et al.*, 2002), a result not easy to account for with language, which would not predict an effect of enclosure size.

A major outstanding question is the role of disorientation in producing the disregard of colour. In the blue wall tasks participants turn (or are turned) on the spot for up to 30 seconds with eyes closed before searching. On Spelke's account disorientation is crucial for activating the "geometric module". This specialised process, which becomes active when orientation is lost, disregards colour.

Rodent studies however suggest that disorientation by turning has specific effects on neural codings of space. Hippocampal place cells code for place unreliably in environments experienced after disorientation (Knierim, Kudrimoti, & McNaughton, 1995), and landmarks are used less effectively by disoriented rats in appetitive Morris tasks (Gibson *et al.*, 2001; Golob & Taube, 2002). This literature suggests some reasons why the disorientation procedure itself – turning on the spot with eyes closed – might contribute to the poor use of the landmark, *i.e.* the blue wall. Explanations derived from this literature could potentially refine the "geometric module" thesis by defining it in terms of neural information processing, or supersede it altogether.

To understand the effect of disorientation better, the disorientation process itself needs to be characterised more carefully. Pilot studies 1 and 2 aimed to separate two aspects: the vestibular *etc.* cues arising from prolonged turning on the spot, which might disrupt neural codings of place and heading, and the state of not knowing one's own orientation within the environment. These studies aimed to separate these two aspects of disorientation by devising a virtual analogue of the "blue wall" environment. In this space subject's facing directions could be manipulated independently of their own movements. Therefore "virtual" disorientation (without turning) could be compared with disorientation in which, as in the original studies, participants spent 30 seconds turning on the spot with eyes closed.

However the technology used for these studies did not enable them to address the question of disorientation adequately. The virtual space was not immersive, but was presented on a computer screen in a dimly lit room. Therefore even physically "disoriented" subjects had first to reorient (within the room) and find the computer. In these studies verbally shadowing subjects who were disoriented did not disregard the colour cue. However this result could be explained by the fact that by the time they

made their response, they were no longer really disoriented. These pilot studies are described in Appendix 1.

One observation of the behaviour of disoriented subjects in pilot studies 1 and 2 (see Appendix 1) was of interest. In the dimly lit room, disoriented subjects who had opened their eyes often started walking in the wrong direction towards the computer, before seeming surprised and stopping to correct themselves. It seemed that some erroneous representation of direction was present for long enough to drive a motor response. This might happen if disorientation by turning did not *eliminate* the sense of heading, but set it to a random direction, and this random heading cue continued to exert some effect on behaviour for a short period. Once subjects opened their eyes they could begin to correct their sense of heading using visual evidence. However in a small enough room, such as Hermer and Spelke's enclosure, a subject might act so quickly that her representation of heading did not have time to catch up. The disregard of colour could occur if, during this period, geometry exerted a stronger effect in correcting the erroneous heading than did colour.

Why would geometry exert a stronger effect than colour? On Spelke's account, this bias just happens to be a property of orientation. It could perhaps be explained as an evolutionary adaptation appropriate to mammalian environments. However if we suppose that the directional sense post-disorientation might act as an additional cue, this suggests fuller explanations, which derive from the information processing requirements of the task.

The task is to reconcile 1. a (typically erroneous) sense of direction with 2. visual cues to room shape, and 3. visual cues to room colour. Perhaps colour has little effect because an unevenness in the distribution of geometric and colour cues, intrinsic to the enclosure's design, favours the use of geometry.

It has been proposed that a subject must, on every trial, adjust a (random) internal sense of heading by between 0 and 180 degrees, depending on the size of her orientation error. In the Cheng / Hermer & Spelke enclosure, there is a mismatch between the ease with which the heading cue could be reconciled with colour and with geometry: the enclosure contains a geometric ambiguity but not a colour ambiguity. Whichever direction a disoriented subject believes she is facing, she needs to adjust her sense of direction by 90° at most before visual geometry matches what she expects to see. This is because there are two geometrically equivalent views of the room. By contrast, to match her sense of heading with colour, she must make adjustments of up to 180°. In other words, adopting a new orientation correct with

respect to geometry never requires an adjustment greater than 90°, whereas adopting an orientation correct with respect to colour requires adjustments of up to 180°.

Studies with hamsters and mice have shown that visual cues are given priority where these conflict with an internal directional cue as long as the conflict is less than around 90°. When the conflict is greater, animals tend to ignore environmental cues and fall back on their internal sense of heading and location (*i.e.*, path integration) (Etienne, Teroni, Hurni, & Portenier, 1990; Alyan & Jander, 1994). This suggests that in the Cheng enclosure, rodents could use geometry reliably, as it never requires a reorientation of more than 90°, but not colour, which would on average require reorientations greater than 90° half of the time. If rats (or children) reoriented with respect to visual cues as well as they could within a limit of roughly 90°, then approximately half of the time they would search at the wrong but geometrically equivalent location in the Cheng / Hermer & Spelke enclosure. On this interpretation, there might be nothing special about geometry besides its privileged status in the design of the enclosure. Surprisingly, the obvious control, an enclosure in which colour but not geometry is ambiguous, seems not to have been run (but see Experiments 4 - 5).

The foregoing arguments depend on the premise that subjects who have been disoriented by turning retain a random directional sense which continues to exert an effect on behaviour. At this stage this conjecture is based on an informal observation. The next set of studies (experiments 1 – 2) measure the effect of such an internal directional cue on shadowing adults in enclosures similar to Hermer & Spelke's.

2.4 Experiment 1

Perceived heading directions are usually inferred from search behaviour. With animals or young children, who cannot report which way they think they are facing, this is the only approach. In the blue wall task we need to measure how subjects' perceived sense of direction in the room, while still disoriented and *before* they see visual cues and select a search location, influence which location they search. Measuring these initial orientations behaviourally would be difficult. One approach would be to extend the period of no vision and to measure initial movements before eyes are opened or lights are turned on. As well as being difficult, such an experiment might not be valid. Allowing subjects to make initial movements without vision would be likely to increase their use of the internal directional sense, making this a poor basis for assessing its use in the original task.

However the perceived heading directions of human adults are readily elicited by pointing, *i.e.* asking subjects to point to where they think some landmark is. In previous "pointing" studies, subjects could indicate all locations around them, including those behind them (*e.g.* Farrell & Robertson, 1998). The following experiment retained adults as its subjects. Adults provide a good test case for the hypothesis in any case. If erroneous directional cues had a measurable effect on adult search behaviour, there would be good reason to suppose that the same effect might also operate in less cognitively sophisticated subjects.

Although adults, being capable of pointing, can have their perceived orientations measured without being allowed to start a search response, a concern remains that merely asking subjects to judge their heading could have the effect of producing in them a directional sense that would otherwise not be present. For this reason non-pointing control conditions were included. As long as patterns of error did not differ between pointing and non-pointing trials, it would be safe to assume that the pointing task itself did not influence performance.

This experiment took place in an enclosure with one blue wall, modelled on Hermer & Spelke's. On each trial, a participant was either shadowing or not shadowing, and either pointing or not pointing. As in the original studies, after seeing an object hidden participants were always disoriented by turning. On pointing trials, disoriented subjects were first asked to point, while still blindfolded, to where they thought the object was.

Method

Subjects

26 undergraduate native English speakers (12 male; mean age 20.1, sd 1.7 years) took part in the study. None were excluded (see *Analysis* and *Results*).

Apparatus

A 231 x 169 x 185cm rectangular chamber, composed of fabric stretched over a concealed metal frame, was situated within a larger experimental room with no sources of light or noise. Three longer walls and one shorter wall were white, while the other shorter wall was blue; see *Introduction*,
Figure 1 b (p. 33). White fabric was stretched across the top of the frame to create a ceiling, and the floor of the chamber was covered in unpatterned linoleum. A grey cardboard screen 110cm high stood in each corner, with a receptacle concealed behind and close to the top of each so that an object could be hidden there. The room was lit by four 40 Watt lights, one at the top centre of each wall. Participant and experimenter entered and exited through one of the walls, which was drawn aside to create an opening and re-sealed using Velcro during the testing.

The hiding object was a small colourful ball. Participants wore a blindfold which could easily be raised and lowered. The shadowing stimulus, plus low continuous white noise to mask any external orienting sound, were played through wireless headphones. In the nonshadowing conditions only the white noise was heard. A microphone recorded verbal performance on the shadowing task. Political and business articles from The Times were chosen. On initial piloting the stimulus was too difficult to shadow. Linda Hermer (personal communication) also judged it to be too fast. The articles were read out more slowly for a second recording, but with agaps greater than 0.5 seconds cut to 0.5 seconds to restrict subjects' opportunities to pause. The final stimulus could be shadowed in real time by most subjects, although not without clear effort.

Design

The experiment had four conditions in a 2x2 (shadowing / not shadowing, pointing / not pointing) within-subjects design, with subjects randomly assigned to one of four orders. Either the first two blocks or the last two blocks included shadowing, while either the middle two blocks or the first and last block included pointing. Both shadowing blocks therefore always occurred consecutively (since shadowing required

a two minute "warm up" period), and no more than one task requirement, shadowing or turning, changed between one block and the next.

Each block had four trials. Hiding locations were randomised so that each block included all 4 locations, and no block began with the location on which the last ended. Walls faced after disorientation were also randomised so that each wall was faced once in every block.

Procedure

Apart from the pointing task, the procedure was equivalent to Hermer-Vazquez *et al.* (1999). On each trial, subjects saw the object hidden in one of the corners, then lowered their blindfold and turned on the spot in the centre of the room for 30 seconds, the experimenter walking around and tapping the subject to signal changes of direction. On shadowing trials, subjects did the verbal shadowing task concurrently. Prior to the two shadowing blocks, subjects started shadowing outside the chamber, continuing until they were competent. Without stopping shadowing, they then entered the chamber and began the main task. On pointing trials subjects who had just stopped turning were asked, while still blindfolded, to point to where they thought the object was. The experimenter recorded the direction of each point on a schematic of the room. All trials ended with subjects raising the blindfold and searching for the object.

To avoid distracting subjects from their shadowing with verbal instructions, all instructions during the experiment were nonverbal, using codes practiced beforehand. After hiding the object, the experimenter mimed the action of putting the blindfold down to instruct the subject to do the same. After turning, the experimenter raised the subject's blindfold. On pointing trials this was preceded by tapping the subject's hand to indicate that a point was required.

Analysis

Each search was coded, C, N, R or F according to Hermer and Spelke's scheme, illustrated in Figure 2.

Hiding place ***Possible search locations***

"Geometrically correct": C + R
"Colour correct": C + N

Figure 2. *Coding scheme for searches. Left: example trial on which the object is hidden in the corner marked "*". Right: coding for each of the four possible search locations. C: correct; R: rotational equivalent; N: near corner; F: far corner. C and R searches are "geometrically correct" as the geometry cue matches. C and N searches are "colour correct" as both bear the same relation to wall colour (both are either at a white-blue corner, as in this example, or at a white-white corner).*

Rates of C, C+R and C+N search were compared with chance, and effects of the two factors, *pointing* and *shadowing*, were tested in a repeated-measures ANOVA.

Recordings of shadowing were examined to identify any gaps greater than 2 seconds, in which subjects might have been able to form verbal descriptions of the hiding place.

Pointing angles were measured from the paper schematics on which they were recorded. For each trial, two measures were calculated from these (Figure 3). *Pointing error* was the absolute angle, in degrees, between the subject's estimate of where the object was and its real location. *Search from point* was the absolute angle between the subject's blindfold estimate of where the object was and their choice of search location after removing the blindfold.

The first measure, pointing error, was used to check that participants were disoriented. An absolute pointing error can range from 0° to 180°. The average for a large set of random angles between 0° to 180° would be 90°. Therefore mean pointing error in disoriented participants should not be significantly below 90°, the average expected by chance. A mean pointing error below 90° would show that participants still had some information about the object's location.

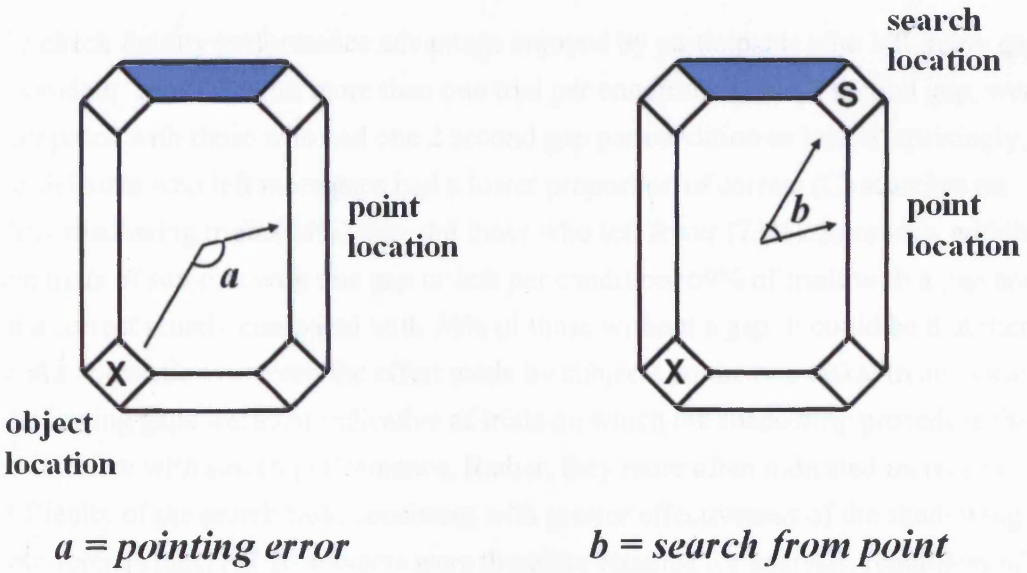


***Figure 3**. Calculation of the two pointing measures. On each trial participants were asked to point to where they thought the object was, while still disoriented. Pointing error (left) was calculated as the unsigned angle between the point and the true location of the object. Search from point (right) was calculated as the unsigned angle between the point and the participant's eventual search location, after the blindfold was removed. On a correct search, b = a.*

The second measure, search from point, was used to evaluate whether the direction pointed in while blindfolded was a significant predictor of the place subsequently searched. Possible angles between places pointed to and places searched range from 0° to 180°, and if there was no relation between these measures a mean angle of 90° would be expected. The prediction in this study was that participants' sense of where the object was while still disoriented would influence their choice of search location. That is, mean search from point would be lower than the 90° expected by chance.

Results

Shadowing performance

Subjects showed a poor ability to shadow uninterrupted for the 8 shadowing trials in this experiment. Only four of 26 met the criterion of leaving no gap greater than 2 seconds over the 8 trials. Fourteen of 26 had a 2 second gap on no more than one of four trials for each of their two shadowing conditions. One possibility was to analyse only these subjects, omitting their "gap" trials from the analysis. This approach would however mean rejecting nearly half the subjects.

To check for any performance advantage enjoyed by participants who left many gaps, candidate "rejects", with more than one trial per condition with a 2 second gap, were compared with those who had one 2 second gap per condition or less. Surprisingly, participants who left more gaps had a lower proportion of correct (C) searches on their shadowing trials (64%) than did those who left fewer (73%). Likewise, within the trials of subjects with one gap or less per condition, 69% of trials with a gap ended in a correct search, compared with 94% of those without a gap. It could be that there was a correlation between the effort made by subjects on the two tasks. In any case, shadowing gaps were not indicative of trials on which the shadowing procedure failed to interfere with search performance. Rather, they more often indicated increased difficulty of the search task, consistent with greater effectiveness of the shadowing interference task. All 26 subjects were therefore retained for analysis, regardless of shadowing performance.

Patterns of search

Figure 4 shows the rate of search at each corner by condition. It was predicted that shadowing subjects would disregard the colour cue, but that the pointing demand would not influence performance. Neither prediction was met. First, no condition showed a failure to differentiate between C and R corners. The condition matching the shadowing condition in the original study (Figure 4, top right) showed a reliable preference for the correct corner (76.9%) over its rotational equivalent (8.7%). Second, the pointing demand led to reductions in performance slightly greater than the shadowing demand, and additive with it.

Binomial tests confirm that rates of both "geometrically correct" (C+R) and "colour correct" search (C+N) were greater than chance (50%) on every condition (for all conditions, $p < 0.001$). A repeated-measures ANOVA found a significant effect of pointing, $F(1, 25) = 8.5$, $p < 0.01$ on the rate of correct search, but no significant effect of shadowing, $F(1, 25) = 2.8$, $p = 0.11$, and no interaction.

Not shadowing & not pointing

C		F
	82.7 1.9	
	10.6 4.8	
N		R

C+R = 87.5
C+N = 93.3

Shadowing & not pointing

C		F
	76.9 1.0	
	13.5 8.7	
N		R

C+R = 85.6
C+N= 90.4

Not shadowing & pointing

C		F
	73.4 5.1	
	10.9 10.6	
N		R

C+R = 84.0
C+N = 84.3

Shadowing & pointing

C		F
	62.2 7.7	
	11.5 18.6	
N		R

C+R = 80.8
C+N = 73.7

Figure 4. *Rates of search (%) on the blue wall task, under verbal shadowing (right), non-shadowing (left), pointing (bottom) and not pointing (top) conditions.*

A practice effect?

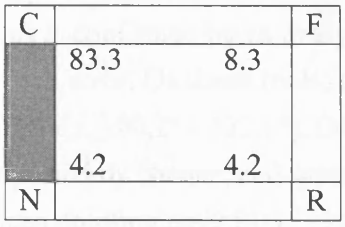
Figure 4 shows a failure to replicate Hermer & Spelke's "selective disregard of colour when shadowing" result. As in the virtual studies, the condition most closely matching theirs (shadowing and not pointing; top right) had more errors consistent with colour but not geometry (N) than errors consistent with geometry but not colour (R).

However a difference between the tasks needs to be considered. Hermer & Spelke's subjects always did the shadowing condition first, for a total of four trials. By contrast, the order in this study was randomised. Therefore many subjects were already experienced with the enclosure by the time they were tested while shadowing. It could be that this gave them a chance to learn the layout and the task.

Data from only the first block for each subject (Figure 5) suggests that there was indeed a practice effect. For the seven subjects who experienced it first, one of our conditions, shadowing and pointing (bottom right) showed the effect reported by Hermer and Spelke, subjects searching with respect to geometry but not the colour

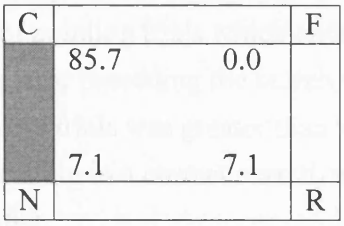
cue. For those subjects the rate of "colour correct" (C+N) search, 52.4%, did not differ from the 50% predicted by chance (binomial $p > 0.4$). However those subjects who did the non-pointing shadowing condition which matches the original first (top right) did not show this effect at all (C+N rate = 92.9%; binomial $p < 0.001$).

Not shadowing & not pointing; Naïve subjects only (N=6)



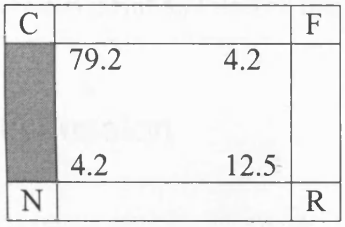
C+R = 87.5
C+N = 87.5

Shadowing & not pointing; Naïve subjects only (N=7)



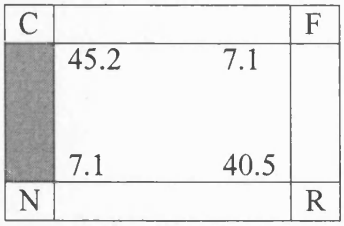
C+R = 92.9
C+N= 92.9

Not shadowing & pointing; Naïve subjects only (N=6)



C+R = 91.7
C+N = 83.3

Shadowing & pointing; Naïve subjects only (N=7)



C+R = 85.7
C+N = 52.4

Figure 5. *Rates of search (%) from trials in each participant's first block only. Each condition shows data from a different group of subjects, those who experienced that condition first.*

Effects of perceived heading

Since pointing significantly increased the rate of error, it cannot be ruled out that asking participants to judge their orientation caused them to adopt erroneous orientations that influenced search. The pointing measure will therefore be inconclusive, at least in this initial study, but was analysed in any case.

On average, subjects pointed 90.3° (95% confidence interval 83.1° – 98.3°) away from the target. This figure, very close to the 90° predicted by chance, confirms the

effectiveness of the disorientation procedure. Having removed the blindfold, subjects searched an average 75° (95% c.i. 67.4° - 83.3°) away from the direction pointed to. The upper bound of the confidence interval excludes 90°: searches were therefore significantly closer on average to the directions pointed to than would be expected by chance. This confirms that even though subjects' points were not predicted by where the object really was, the points in turn predicted where they would subsequently search. This means that searches close to the place pointed to must have accounted for some of the search errors.

This is confirmed by an analysis of the subset of pointing trials which ended with a search error. On these trials, the mean pointing error preceding the search was 111.1° (95% c.i. 100.2° - 122.1°). Disorientation on these trials was greater than would be expected by chance, and greater than on trials ending in a correct search, which had mean pointing error 81.1° (95% c.i. 71.5° - 90.6°).

Erroneous searches also tended to be closer to the place pointed to, at a mean distance of 63.3° (95% c.i. 49.1° - 77.6°), than did correct searches, with mean distance 81.1° (95% c.i. 71.5° - 90.6°; for all correct searches, the pointing error and the distance between point and search are the same).

Discussion

Subjects' problems with maintaining the shadowing task without gaps suggests that it was difficult enough, yet it did not produce the disregard of geometry observed by Hermer and Spelke. Indeed, if that effect emerged at all, it was only in conjunction with the pointing task, in a subgroup of subjects for whom the first experience of the enclosure involved both pointing and shadowing.

The pointing data showed that subjects' perceived headings with respect to the hidden object were a significant predictor of subsequent search location, both overall, and (even more so) on trials ending in a search error. This is consistent with the thesis that disoriented subjects possessed a random directional cue which had to be reconciled with visual information, incomplete reconciliations resulting in search error. However the increased rate of error in the pointing conditions prevents any strong conclusion from being drawn. It could be that being asked to point cued subjects to search in the direction pointed to. Furthermore, these results do not directly explain the selective disregard of geometric information in the previous studies, as in this experiment geometric information was (overall) not disregarded.

2.5 Experiment 2

Experiment 2 made a second attempt in a real enclosure to replicate Hermer and Spelke's shadowing result. As in the preceding study, subjects' senses of direction post-disorientation were probed with a pointing measure. However the mode of instruction was changed from nonverbal to verbal, and a new control was added to the pointing task.

In Experiment 1, shadowing subjects had to understand instructions given in mimes and hand taps. They tended to respond quite slowly, perhaps because they needed time to interpret each instruction, and perhaps because these nonverbal communications from the experimenter did not convey much urgency. In further piloting a method closer to the original, using verbal instructions, was found to be much better for eliciting speeded responses. Instructions to "find the object!", and warnings to "keep shadowing!" at any sign of stopping, were reported to be quite stressful, and seemed to convey the need to find the object quickly. It was also hoped that verbal instructions might be easier to follow than those experiment 1, where one explanation for the increased error in the pointing conditions would be that subjects were confused by the additional demand to remember what the tap meant.

A further possible confound of the pointing procedure in experiment 1 was that merely pointing somewhere might cue subjects to search in that direction. In the present study, this was checked with a control condition in which subjects pointed towards somewhere other than the object: the blue wall.

Comparing the accuracy of the object-point and wall-point measures could also show whether disoriented representations of heading influenced subsequent search because they directly represented where the object was relative to the subject, or because they represented where the subject was facing within the enclosure.

If subjects tended to track, egocentrically, where the object was relative to them, the object-point measure should be more accurate. If they tracked where they were within the framework of the enclosure, the wall-point measure should be more accurate.

Subjects in this study shadowed on all trials. On each trial they were asked to point either to the object, or to the blue wall, or neither, or both.

Method

Subjects

25 undergraduate native English speakers took part in the study. One subject unable to do the shadowing task, and two who did not become disoriented (see *Results*), were excluded, leaving 22 (11 male) with mean age 24.1 (s.d. 4.2) years.

Apparatus

The testing enclosure, headphones and shadowing stimuli were the same as for experiment 1.

Design

There were four conditions in a 2x2 (pointing to the blue wall / not pointing to the blue wall; pointing to the object / not pointing to the object) design. Subjects shadowed on every condition. There were four blocks of four trials. Each block included all four conditions in a random order. Hiding locations and facing walls were randomised in blocks as before. For trials in which both the object and the wall were pointed to, the order in which these points were elicited (object first or wall first) alternated from block to block, with the order for block 1 selected randomly.

Procedure

As before, subjects practiced the shadowing task before entering the enclosure. Once inside, they saw an object hidden on every trial. After turning blindfolded in the centre for 30 seconds, subjects were told to point to the object, the blue wall, both in turn, or neither (in which case this stage was skipped). Point directions were recorded on a schematic of the room. Subjects were then asked to remove the blindfold and find the object. Those who paused were reminded to "keep shadowing!"

Analysis

Rates of C, C+R and C+N search were compared with chance as before. Effects of having to pointing to the wall or to the object on rates of correct search were analysed in a repeated-measures ANOVA.

"Pointing error" and "search from point" measures (see *Experiment 1 / Analysis*; p. 39) were calculated separately for each of the two kinds of point. On point to the blue wall (only) trials, an additional measure was calculated: the angle between the corner searched and the place where the object theoretically *would* be, if the wall-point were correct. This "search relative to wall point" measure could be an indirect indicator of the effect of perceived orientation on subsequent search. All five measures were

compared with chance (90°). The wall- and object-pointing error measures were also compared with each other, to see if one was more accurate.

Since gaps did not previously indicate ineffectiveness of the shadowing procedure, shadowing performance in this experiment was not recorded or analysed.

Results

Shadowing performance and disorientation

One participant was unable to do the shadowing task at all, and stopped the experiment before entering the enclosure. Consistently high pointing accuracy in two other subjects, better than chance at the 99% level, indicated that they were not disoriented. These subjects were excluded from analysis.

Patterns of search

Figure 6 shows rates of search by location in each of the four pointing conditions. Once again, these results did not show any failure to use the colour cue. Rates of correct search were high, while rotationally equivalent R searches were consistently low, N errors being more common in every condition. As in Experiment 1, rates of both "geometrically correct" (C+N) and "colour correct" search (C+N) were above chance (50%) in every condition (for all conditions, $p<0.001$).

Unlike in Experiment 1, the demand to point was not associated with increased search error. In fact, the condition in which there was no pointing at all (Figure 6, top left) showed the highest rate of error. A within-subjects ANOVA found no effect of the demand to point to the object ($F(1, 21) = 0.04$, $p > 0.8$), no effect of the demand to point to the blue wall ($F(1, 21) = 2.0$, $p > 0.1$), and no interaction ($F(1, 21) = 2.1$, $p > 0.1$).

Search rates for the first block only, in which subjects were inexperienced with the enclosure, were also examined as in Experiment 1. This time there was no evidence for a high rate of R search in naïve subjects. Although rates of R search were higher for the first block, the C and R search rates did not approach each other in any condition.

Point to neither

C		F
	64.4 8.0	
	18.4 9.2	
N		R

C+R = 73.6
C+N = 82.8

Point to the object

C		F
	71.6 8.0	
	15.9 4.5	
N		R

C+R = 76.1
C+N= 87.5

Point to the blue wall

C		F
	77.3 2.3	
	11.4 9.1	
N		R

C+R = 86.4
C+N = 88.6

Point to both

C		F
	72.1 5.8	
	12.8 9.3	
N		R

C+R = 81.4
C+N = 84.9

Figure 6. *Rates of search (%) under pointing to the object (right), not pointing to the object (left), pointing to the blue wall (bottom) and not pointing to the blue wall (top) conditions.*

Effects of perceived heading

Two heading measures were available: the object point, measured on half of all trials, and the wall point, also measured on half of all trials; a quarter of trials included both.

95% confidence intervals for both these estimates of heading included chance (90°), confirming that subjects (excluding the two excluded from analysis because they maintained their orientation very accurately) were successfully disoriented. Points to the object were an average 91.0° (95% c.i. 83.1° - 98.9°) off target. Points to the blue wall were off target by an average 85.5° (95% c.i. 78.0° - 93.0°).

On object-pointing trials, subjects searched an average 80.4° (95% c.i. 72.2° - 88.6°) from the direction pointed to. On the subset of these trials that ended in a search error, this distance was 63.9° (95% c.i. 48.6° - 79.2°). Therefore as in Experiment 1, after visual information became available subjects still searched significantly closer to the place where they initially thought the object was than would be expected by chance.

On "point to the blue wall" trials, searches were an average 84.2° (95% c.i. 76.4° - 91.9°) away from the point. Considering only those trials ending in a search error, this figure was 81.0° (95% c.i. 65.1° - 96.8°). Unlike points to the object, points to the wall did not predict searches close to the place pointed to, either overall or on error trials in particular.

These results confirm that the mere act of pointing somewhere was not sufficient to cue a search in that direction. Disoriented points only predicted subsequent directions of search when they were to the perceived location of the hidden object.

The final pointing measure was "search relative to wall point". This was, on trials with only a point to the wall (a quarter of all trials), the angle between the corner searched and the direction in which the object *would* be, if the wall-point had been correct. On average, subjects searched 88.2° (95% c.i. 80.7° - 95.8°) from this direction. On the subset of trials ending in an incorrect search, searches were 102.0° (95% c.i. 85.1° - 118.8°) from this direction. As both these confidence intervals include chance, these results show no effect for this indirect measure of heading as a predictor of search.

Accuracy of object- and enclosure-based judgments of heading

Results so far show that disoriented subjects had some representation of orientation (heading) that influenced subsequent search. A crucial question is whether they 1. tracked the position of the hidden object egocentrically as they turned, or 2. tracked their own orientation within the framework of the enclosure while remembering (allocentrically) where the object was within the enclosure (*e.g.* where it was with respect to a landmark, the blue wall). By comparing the accuracy of wall-points and object-points, the basis for subjects' representations of heading could be assessed.

A difficulty is that by aiming to induce total disorientation, whether judged relative to object or blue wall, the experiment was not well designed to find an accuracy difference in judgments of wall and object direction. If both were chance, they should not differ. In fact, the trend was for judgments of wall direction to be slightly more accurate (mean error 85.5°) than object direction (mean error 91.0°); however these did not differ significantly ($t(346) = 1.0$, $p > 0.3$).

Fortunately there were two subjects, excluded from analysis so far, who did not become fully disoriented. These are exactly the kind of subjects needed for this

comparison. For these two, whose data include a total of 16 object-points and 16 wall-points, mean object-point was 71.1° from the corner with the hidden object, while mean wall-point only 20.8° from the centre of the blue wall. The difference in accuracy was significant ($t(30) = 2.8$, $p < 0.01$). These two subjects, who maintained their orientation, therefore maintained it much more accurately with respect to the allocentric framework of visual features in enclosure, than with respect to the egocentric location of the hidden object.

Discussion

It was predicted that verbal instructions would decrease the error associated with pointing. It was also hoped that with speeded verbally elicited responses, the disregard of colour in shadowing adults would be replicated.

As predicted, pointing in this study was not associated with increased search error. This supports the interpretation that pointing subjects in Experiment 1 were distracted by having to interpret hand taps. Heading directions elicited by points in this experiment could be assumed to be free of confounding effects on subsequent search.

However there was still no evidence for a selective disregard of colour. Although they were shadowing throughout, subjects used both colour and geometry to search. The subset of "naïve" trials (those on in each subject's first block) likewise showed use of both colour and geometry.

The pointing measures confirmed that disoriented estimates of where the object was predicted locations of search once visual information became available. A control point, not towards the object but towards the blue wall, was not a predictor. The predictive effect of the object-point therefore cannot be explained as some simple property of pointing, such as acting as a preparatory reach to cue subjects towards a particular direction.

Most subjects were completely disoriented by the time they pointed. There was a nonsignificant trend for points to the wall to be more accurate than points to the object. However in two subjects who did not become disoriented, wall-points were much more accurate than object-points. This suggests that subjects' primary representations of own orientation were with respect to the reference frame of the enclosure, and not towards the hidden object. The place of the wall could therefore be

accessed directly, and more accurately, whereas the place of the object could only be accessed indirectly, and less accurately.

This is especially interesting considering that the blue wall was a much wider target to point to than the corner with the object. The instruction to "point to the blue wall" could have been interpreted to mean to point to any part of it. When pointing errors were calculated, they were measured from the exact centre of the wall. Therefore in two subjects who were not disoriented, and nonsignificantly in the rest, the wall-pointing measure was more accurate even though it was specified less accurately.

Whether an "enclosure based" representation of orientation might influence search was assessed with one more measure: on pointing to the blue wall (only) trials, were searches close to the place where the object *would* be, if the blue wall point had been correct? This location did not predict search. However, the logic of the prediction itself is flawed. To search using an erroneous (disoriented) representation of the place of the blue wall, subjects who have opened their eyes would have to disregard the visual evidence to the true place of the very feature to which their attention had just been drawn. This pattern of behaviour, favouring an imaginary landmark over its real counterpart, would be very strange example of landmark use, and it is not surprising that it was not observed.

2.6 Experiment 3

The aim of Experiment 3 was to provide a better measure of the effect of perceived heading *within the enclosure* on subsequent search. A measure of orientation in room-centred coordinates (*e.g.*, "North" in the reference frame defined by the enclosure) was used whose effect on search location could be examined without confound. The confound in the previous study was that erroneous estimates of "North" were disconfirmed once subjects opened their eyes. In this study subjects would not always know whether their judgment of heading had been correct.

The landmark was changed from a permanent coloured wall to a coloured light which illuminated one of the walls from outside the enclosure, and could be switched on or off by the experimenter. Disoriented subjects' sense heading was elicited by asking them to judge where the light was. The critical trials were those on which the light was absent when subjects opened their eyes. There was now no landmark to confirm or disconfirm perceived heading. Only the geometric cue (enclosure shape) remained, making this task equivalent to Hermer and Spelke's enclosure with four white walls,

where the correct corner C and its rotational equivalent R are visually indistinguishable. A subject using geometry would search these at high and similar frequency. This study would determine whether the sense of orientation in disoriented subjects was a good predictor of which of the two visually indistinguishable corners they would choose on each trial.

An alternative predictor is facing direction: given two indistinguishable target corners, subjects might just choose the one that is closer to straight ahead and therefore slightly easier to reach. However if perceived heading is as important as has been hypothesised, heading should be a better predictor than facing direction.

Preliminary results from a pilot study suggested that 10 seconds of turning were sufficient to reduce subjects' accuracy at estimating heading to near chance, but that these subjects, although no better oriented than those who had turned for 30 seconds, were more confident about their estimates of heading. Accordingly, a second factor in this study was turning time, 10 or 30 seconds. An interesting result would be if points were better predictors of search after 10 than after 30 seconds. This would be consistent with an effect of heading confidence strong enough to counter the memory advantage of a shorter interval. In any case, the shorter turning time made it possible to include more trials.

Subjects shadowed on all trials. The coloured wall was always present at the time of hiding. At retrieval, it was either present or absent. Before opening eyes and seeing whether the coloured wall was present or absent, subjects on all trials were asked to point to the light. For a subject in the centre of the enclosure the angle to the light always corresponds to the angle to the centre of the coloured wall. The demand to "point to the light" was therefore equivalent to being asked to "point to the blue wall" in the previous study.

Although coloured wall-absent trials were of main interest, the coloured wall remained present half the time to maintain interest in it as a cue. Subjects who learnt that the coloured wall was never present at retrieval might stop attending to it.

Method

Subjects

20 undergraduates and individuals from the UCL volunteer database took part. All were native English speakers. Two subjects who did not become disoriented were excluded from analysis, leaving 18 (7 male) with mean age 24.8 (s.d. 8.8) years.

Apparatus

The apparatus was the same as for the previous two experiments, except that all four walls of the enclosure were white, and a very bright 500W halogen light fitted with a green filter was directed at one of the enclosure's two short walls from outside. When switched on, this light coloured that wall green. It was operated from inside the enclosure using a switch concealed behind one of the four corner panels. The enclosure's four inside lights were changed from 40W to 25W to increase the contrast between white walls and the green wall.

Design

The coloured wall was always present at hiding. The experiment had four conditions in a 2 x 2 (coloured wall present at retrieval / absent at retrieval; 10 second disorientation / 30 second disorientation) design. Subjects completed six blocks of four trials, each block including one trial from every condition in random order. Hiding locations and facing directions were also randomised in blocks as before.

Procedure

Before starting the study, subjects were shown the light outside the enclosure. It was pointed out that there was only one light, and that they should therefore assume the light to be stable, and not to illuminate different walls at different times.

The procedure was the same as before, except that the experimenter also manipulated the light. On each trial, after the object had been hidden and the subject had put on the blindfold and started turning on the spot, the experimenter either operated the light switch, turning off the light, or pressed a dummy switch which had no effect. The purpose of the dummy was to prevent subjects from using the sound of the switch to guess whether the light would still be on or not at the end of each trial. After 10 seconds or 30 seconds of turning, subjects were stopped facing a predetermined wall. They were asked to point to where they thought the light was, then to remove the blindfold and search.

Analysis

Search results from coloured wall-present and -absent conditions were treated separately, as they represent different tasks. With the disambiguating colour cue present, 100% correct performance could be achieved. These conditions amount to a repeat of the pointing to the blue wall (only) condition in the previous study, with an added duration of turning factor. With the colour cue absent, optimal performance (given complete disorientation) would be a 50-50 split between the visually indistinguishable C and R corners.

The critical measure derived from subjects' pointing directions was the direction in which the object *would* be, if the point to the light were correct. Mean angles between this place and the place searched were compared with chance. Of particular interest were the coloured wall-absent conditions, where no colour cue was available to disconfirm erroneous estimates of orientation.

Results

Shadowing performance and disorientation

No subjects had problems with the shadowing task. Two did not become reliably disoriented, showing mean pointing errors better than chance at the 99.9% and 99.99% levels. These were excluded from further analysis.

Patterns of search

Figure 7 shows rates of search for the four conditions. As in the previous studies, when a colour cue was available (top row), subjects used it successfully to disambiguate the C and R corners. When no colour cue was available (bottom rows), rates of C and R search were closer, although the higher rate of C search in subjects who were only disoriented for 10 seconds (bottom left) suggests that their disorientation may not have been complete.

Mean rates of correct (C) search and geometrically correct (C+R) search were better than chance on binomial tests (for C search, $p < 0.001$ for every condition except absent / 30s, where $p < 0.01$; for C+R search, $p < 0.001$ for every condition). Rates of C+N search, consistent with use of the colour cue, were above chance for both the light present conditions ($p < 0.001$). They were not significantly above chance in the light absent conditions, where this cue was not available at retrieval (for 10 seconds, $p > 0.1$; for 30 seconds, $p = 0.08$).

Coloured wall present, 10 seconds

C		F
	64.6 9.6	
	9.8 16.0	
N		R

C+R = 80.5
C+N = 74.2

Coloured wall present, 30 seconds

C		F
	58.8 11.4	
	19.3 10.5	
N		R

C+R = 69.3
C+N= 78.1

Coloured wall absent, 10 seconds

C		F
	50.0 16.7	
	5.3 28.1	
N		R

C+R = 78.1
C+N = 55.3

Coloured wall absent, 30 seconds

C		F
	36.8 12.3	
	19.3 31.6	
N		R

C+R = 68.4
C+N = 56.1

Figure 7. *Rates of search (%) with the colour cue present at retrieval (top), absent (bottom); after turning for 10 seconds (left), 30 seconds (right).*

Rates of search were compared for 10-second and 30-second disorientation trials. When the coloured wall was present (Figure 7, top row), the difference between rate of correct search after 10 seconds (64.6%) and 30 seconds (58.8%) was not significant, $t(18) = 1.18$, $p > 0.2$. When the coloured wall was absent (bottom row), the difference between rate of geometrically correct C+R search (*i.e.,* search consistent with the remaining visual evidence) after 10 seconds (78.1%) and 30 seconds (68.4%) likewise did not reach significance, $t(18)=1.91$, $p=0.09$. Taken together, these results suggest at best a minimal advantage, reflected in correct use of the available visual cues, for 10 second disorientation.

Effects of perceived heading

Table 1 shows means and 95% confidence intervals for heading error by condition. In the bottom row, all four conditions are collapsed to give greater sensitivity, *i.e.* a narrower confidence interval. Disoriented judgments of the direction of the light were not significantly better than chance (90°) on any condition, nor on all conditions considered together. Heading errors were compared in a repeated-measures ANOVA.

Neither turning time, $F(1) = 0.12$, $p > 0.7$, nor light presence, $F(1) = 0.20$, $p > 0.6$, had a significant effect on the accuracy of heading judgments, and there was no interaction, $F(1) = 0.20$, $p > 0.6$. These results show that subjects were successfully disoriented, and that the magnitude of their disorientation did not differ across conditions.

Judgments of heading: mean error at pointing to the light	
Light present, 10 seconds	***Light present, 30 seconds***
88.6° (78.3° - 98.8°)	93.6° (82.7° - 104.3°)
Light absent, 10 seconds	***Light absent, 30 seconds***
87.0° (75.9° - 98.2°)	89.1° (78.5° - 99.7°)
Mean across all conditions: 89.5° (84.2° - 94.9°)	

Table 1. *Mean errors (95% c.i.s) in disoriented judgments of where the light was, with the light cue (subsequently) present (top row), absent (second row); after 10 seconds (left), 30 seconds (right); for all conditions together (bottom row).*

The next measure is the mean angle between direction pointed to and corner searched ("search from point"). Since all points were to the light and not the object, this is a control, as before, to confirm that merely pointing somewhere did not cue searches in the direction of the point.

Mean angles between point and search (Table 2) were not significantly below chance for any condition, nor for all conditions considered together. An ANOVA found no effect of turning time, $F(1) = 0.99$, $p > 0.3$, light presence, $F(1) = 0.86$, $p > 0.3$, or any interaction, $F(1) = 0.59$, $p > 0.4$. These results show that points did not predict searches close to the place pointed to, and that the mean distance between place pointed to and place searched did not vary across conditions.

Mean angle between point and subsequent search	
Light present, 10 seconds	***Light present, 30 seconds***
93.1° (82.3° - 103.9°)	84.1° (74.0° - 94.2°)
Light absent, 10 seconds	***Light absent, 30 seconds***
84.4° (74.2° - 94.6°)	83.2° (73.7° - 92.8°)
Mean across all conditions: 86.2° (95% c.i. 81.1° - 91.2°)	

Table 2. *Mean angles (95% confidence intervals) between disoriented judgments of the direction of the light and subsequent searches.*

The crucial measure in this study was the distance between the place searched and the place where the object *would* be, if the estimate of heading within the enclosure (the judged direction of the light) were correct. The light-present conditions replicate an equivalent measure in Experiment 2, where this result was negative. The light-absent conditions provide a novel measure, where the light was no longer available to confirm or disconfirm disoriented estimates of heading. Table 3 shows these distances by condition.

Mean angle between where the object should be according to the disoriented heading estimate, and place of subsequent search	
Light present, 10 seconds	***Light present, 30 seconds***
78.8° (68.7° - 88.9°) *	86.8° (76.5° - 97.1°)
Light absent, 10 seconds	***Light absent, 30 seconds***
67.6° (57.1° - 78.2°) *	73.5° (63.1° - 83.7°) *
Mean across all conditions: 76.7° (71.6° - 81.8°) *	

Table 3. *Mean angles (95% confidence intervals) between the place where the object would be if judgments of where the light was were correct, and subsequent search. * Mean distance below chance at the 5% level.*

As in Experiment 2, subjects who searched after 30 seconds with the coloured wall present (Table 3, top right) were not closer to the place indicated indirectly by their judgment of heading than chance. Interestingly, with the coloured wall present but after only 10 seconds' disorientation (top left) subjects *did* search closer this place than would be expected by chance.

As predicted, when the coloured wall was absent subjects also searched closer than chance to the place indicated indirectly by their judgment of heading (Table 3, second row). The effect was stronger in these conditions than in the 10 second/present condition. An ANOVA comparing mean angles across these four conditions found a significant effect of light presence, $F(1) = 5.56$, $p < 0.02$, but no effect of turning time, $F(1) = 1.77$, $p > 0.1$ and no interaction, $F(1) = 0.42$, $p > 0.8$.

The result that subjects in the 10 second / present condition (Table 3, top left) disregarded the visual evidence, and searched instead with respect to their initial, disoriented perception of the colour cue's direction, is very unusual. It does not mean that the real colour cue was supplanted by an imaginary (disoriented) one, because in the 10 second/present condition, the location correct with respect to the colour cue's real place (*i.e.* the object's *actual* hiding place) was an even better predictor of search: searches were on average 47.4° (95% c.i. 34.0° - 60.8°) from this place. This means that both the real place of the colour cue and the previous (disoriented) perception its place influenced the choice of search location. The disoriented perception's effect was the smaller of the two, but above chance.

The result that both the real direction of the light and its disoriented estimate predicted search would be explained by incomplete disorientation. If subjects retained some of their heading, there would be a correlation between their estimates of where the light was, and the light's true location. It would then follow that both of these measures should predict the same thing. However as Table 1 shows, the heading accuracies of subjects in all conditions, including this one, were no better than chance, ruling out this explanation.

The final analysis examined an alternative predictor of place of search, subjects' facing directions within the enclosure when they opened their eyes. Table 4 shows the mean distance between direction faced and place searched for each condition. Searches were not closer than chance to final facing direction for any condition, nor for all conditions considered together.

Mean distance between facing direction and search	
Light present, 10 seconds	***Light present, 30 seconds***
93.8° (84.8° - 103.0°)	88.5° (79.7° - 97.2°)
Light absent, 10 seconds	***Light absent, 30 seconds***
85.3° (76.6° - 94.1°)	86.2° (77.6° - 94.7°)
Mean across all conditions: 88.5° (84.1° - 92.8°)	

Table 4. *Mean angles (95% confidence intervals) between facing direction and subsequent search.*

Discussion

When the coloured wall was present, subjects once again did not disregard it, even though all were performing a concurrent verbal shadowing task. As the pointing measure of most interest in this study depended on the prediction that the colour cue *would* be used to encode the hidden object's location, as before, the repeated failure to replicate the shadowing result was good for the purposes of this experiment.

The main result from the pointing measure was that disoriented heading judged with respect to a fixed landmark, the external light, did indeed predict the subsequent place of search, when either (1) the light (coloured wall) was subsequently absent, so not able to confirm or disconfirm heading, or (2) the coloured wall was present but the disorientation period was only 10 seconds. The latter result is particularly interesting, as it shows that on some trials subjects' searches were influenced by an erroneous judgment of heading even when the visual cue that should disconfirm that judgment had become available.

There was no significant effect of turning time on the rate of correct search. The result from the pointing measure however does suggest an effect of turning time on the use of heading information. When the coloured wall remained present, 10-second turning resulted in searches consistent with disoriented estimates of heading, whereas 30-second turning did not.

Results from the previous experiment suggested that enclosure-referenced representations of heading, corresponding to a local "North", were maintained more accurately in subjects undergoing disorientation than were object-referenced representations, corresponding to an egocentric vector to the hidden object. Results from this experiment confirmed that like egocentric judgments of heading, allocentric judgements were also predictive of place of search when they could not be immediately disconfirmed. In addition, and very unusually, even allocentric judgments that were disconfirmed could predict search if the disorientation period was only 10 seconds. This suggests a temporal trajectory for the use of allocentric heading information for action in disoriented subjects. The allocentric sense of heading was most strongly linked to action after a short period of disorientation.

2.7 Experiments 1 - 3, General Discussion

If it is true that disoriented subjects have not lost their sense of heading, but possess a random heading that partly determines subsequent action (experiments 1 - 3), a new explanation of the "disregard of colour" phenomenon is available. Colour might be disregarded because it requires subjects to make adjustments of up to 180°, whereas geometrically correct corners are always available within 90°.

However given four failures to replicate the shadowing result (that adults performing a verbal interference task disregard wall colour; Hermer-Vazquez *et al.*, 1999), the difficulty remains that data from these studies do not directly bear on the behaviour they were collected to explain, namely the disregard of colour in shadowing disoriented adults. If subjects making a range of different errors, and not selectively disregarding colour, are partly guided by erroneous heading, it is reasonable to suppose that subjects making the more specific error could be doing the same. However the result from subjects who have not shown this pattern provides only weak evidence for this.

The failure to replicate does, however, raise doubts about the original result (Hermer-Vazquez *et al.*, 1999). A recent study, carried out since the completion of these, sheds some light on the present failure to replicate as well as on the role of verbal interference. Ratliff & Newcombe (2005) also found that adults who were shadowing used both geometry and colour at rates above chance. However errors (and rotational "R" errors in particular) were most frequent when subjects were given minimal instructions before starting the task. In the present studies (experiments 1 – 3) subjects were not only instructed carefully, but had often already spent time doing the task

before the first shadowing trial. The disregard of colour in one subgroup of subjects who were naïve to the task (Experiment 1, p. 43) is consistent with the partial disregard of colour in subjects who had minimal instructions in Ratliff & Newcombe (2005).

A further result from Ratliff & Newcombe's (2005) study was that subjects performing a nonverbal interference task involving visual imagery showed a greater disregard of colour than did subjects performing verbal shadowing. Indeed, with the visuospatial interference task subjects found the hidden object no more often in a room with a blue wall than with no interference in a room with four white walls. The errors made during interference were predominantly rotational ("R") errors. These results confirm that disoriented minimally instructed adults can be made to disregard colour selectively, but that the interference task need not be verbal. In light of these findings, further studies should avoid instructing participants beforehand, or giving them many trials over which to practice the task.

Along with the findings that children do not disregard geometry in larger enclosures (Learmonth *et al.*, 2001, Learmonth *et al.*, 2002) and that nonhuman animals can solve the task (Kelly *et al.*, 1998; Gouteux *et al.*, 2001; Sovrano *et al.*, 2002), Ratliff & Newcombe's (2005) result further undermines the thesis that the ability to use colour in the enclosure depends on language.

CHAPTER 3

The use of geometry and colour for reorientation at 18-24 months

3.1 Introduction

In the experiments described in this chapter, colour cues were manipulated in a variant of the Hermer & Spelke enclosure with 18-24 month old children. The aims of the present studies were to correct a potential bias in the original enclosure's design which could have favoured the use of geometry over colour, and to investigate whether making the colour cue more salient could improve its use. The "geometric module" thesis (Hermer & Spelke, 1996) states that pre-verbal children cannot in principle use wall colours to reorient.

The reasons why the design of the enclosure may be biased are these (see also Chapter 2, Introduction). If a subject who opens her eyes has to reconcile a random sense of heading with the visual evidence, to reconcile it with geometry she never needs to make a "fix" greater than 90°, owing to the enclosure's geometric ambiguity. By contrast, to reconcile it with colour she needs to make a "fix" of between 0° and 180°; greater than 90° half the time on average. Experiments 1 - 3 (Chapter 2) suggested that disoriented subjects do possess a sense of heading that partly determines subsequent action. However in those studies subjects performed well and did not disregard colour (except for one set of naïve subjects in Experiment 1), probably because they had been instructed too comprehensively beforehand (Ratliff & Newcombe, 2005).

To see whether 18-24 month olds *can* use colour to reorient, the enclosure was redesigned so that it was not intrinsically biased against the use of colour. Wall colours and textures were also enriched to maximise their saliency. If reorientation is encapsulated with respect to colour, neither of these manipulations should enable children to use the wall colours to reorient.

3.2 Experiment 4

In this study, 18-24 month olds were tested on the reorientation task in square enclosures with indirect "feature" (colour and pattern) cues on the walls. In the Cheng and Spelke studies, "features" denote all non-geometric orienting cues – including as well as colour, texture and (in rodent studies) odour. In the present study, feature cues were expanded from a single coloured wall to include different colours, textures, and flat shapes.

Features on opposite sides of the enclosure were identical, so that the enclosure looked the same through 180° rotation (Figure 8). Because of this ambiguity, a disoriented subject who made use of the feature cues would search at the correct corner and at its rotational equivalent, but not at the other two. A disoriented subject who was not using the features would search all four corners with similar frequency.

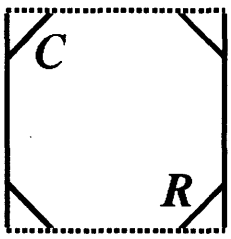


Figure 8. *Above-view schematic of the square enclosure. Pairs of opposite walls are identically coloured and patterned. The correct corner "C" and its rotational equivalent "R" are therefore visually indistinguishable.*

This task is equivalent to Hermer & Spelke's "white room", but with the status of geometry and colour exchanged. In the "white room", colour specified all four corners equally, and geometry specified two corners, 180° from each other, as correct. In this task geometry specified all four corners equally, while features (including colour) specified two corners, 180° from each other, as correct.

A distinction must be made between two spatial factors: geometry and laterality. In this enclosure, the "geometric" cues that were removed (and that young children were reported exclusively to use) were the differing lengths of walls. Using these, young children were previously able to discriminate corners that were left-of-the-long-wall from corners that were right-of-the-long-wall. In the present enclosure all walls were the same length, and the shape ("geometry") of the enclosure therefore did not differ at any of the four corners.

Nevertheless, finding hidden objects still depended on discerning a spatial relation, laterality. Thus in Figure 8, if dotted lines represent blue walls, the correct (but visually indistinguishable) C and R corners are both left-of-the-blue-wall. The incorrect corners are right-of-the-blue-wall. Colour does not indicate the target directly, but only when it is combined with a spatial judgment. This modified enclosure therefore still provides a spatial task in which visual features must be combined with angular information. The indirect visual features distinguishing

different corners do not include relative lengths of walls, previously referred to as "geometry", but this does not mean that the task has no geometric (spatial) element, as children must still make judgments of laterality. The difference is just that to solve this task, a participant must know which colour was on the left, whereas in the "white room" they had to know which wall length was on the left.

The factor varied between conditions was the additional feature information available. Colour, texture, and shape were made progressively richer across three conditions. In the baseline condition ("plain"), the only cues were the coloured walls: two white and two blue, with walls of the same colour opposite each other (see Figure 8). In the "animals" condition, flat pictures of colourful animals and shapes were added to the blue walls. In an intermediate "spots" condition, the colours from these pictures were added to the blue walls in an abstract pattern.

In both "animals" and "spots" conditions, the added shapes were the same on both opposite walls, and symmetrical about the centre of each wall. Each stimulus was also symmetrical about its own midline. Because of these symmetries, the task could not be solved merely by associating the target corner with a particular animal or pattern of spots, but the information provided by these was only useful in conjunction with a correct judgment of laterality. The diagrams in the *Method* make this clear.

It was predicted that children would search at the "feature-correct" C and R corners at rates greater than chance (50%), and that these rates would increase as more feature information was made available. Rates of search at the two corners directly ahead (and therefore immediately visible) were also compared with chance (50%), to test whether what children could immediately see was a better predictor than where features were matched.

Method

Subjects

Subjects were 18-24 month old children recruited from volunteer databases at the Visual Development Unit, University College London, and the Department of Experimental Psychology, Oxford University.

The total number of children tested was 57. Of these, 9 did not complete at least four trials, while two completed at least four trials but were excluded because of a procedural problem, such as failure on the parent's part to cover the eyes properly. 46

completed enough valid trials to be included in the analysis. In the "plain" condition there were 16 (9 male, mean age 21.2, s.d. 2.3 months). In the "animals" condition there were 19 (11 male, mean age 21.0, s.d. 1.1 months). Priority was given to finding sufficient numbers for these two conditions. In the intermediate "spots" condition there were 11 subjects (5 male, mean age 21.0, s.d. 1.0 months).

Apparatus

The enclosure was square with sides of 169cm and height 185cm, composed of fabric stretched over a concealed metal frame, and situated within a larger testing room. Pairs of opposite walls were made of white and blue fabric respectively. For "animals" and "spots" conditions the blue walls had additional flat stimuli made of laminated card attached. Figure 9 shows the layout of the walls for the three conditions.

White fabric was stretched across the top of the frame to create a ceiling, and the floor was unpatterned linoleum. A pink cardboard box with base 22cm^2, height 30cm, and a removable lid stood in each corner. The room was lit by four 25 Watt lights, one at the top centre of each wall. The participant and a parent, who acted as the experimenter, entered and exited through one of the walls, which was drawn aside to create an opening and re-sealed using Velcro for testing. An overhead speaker played a loop of waterfall and bird sounds to mask any uncontrolled external sound. A central overhead camera monitored the experiment. The hiding object was a small toy, brought by the child's parent or selected beforehand in the play area.

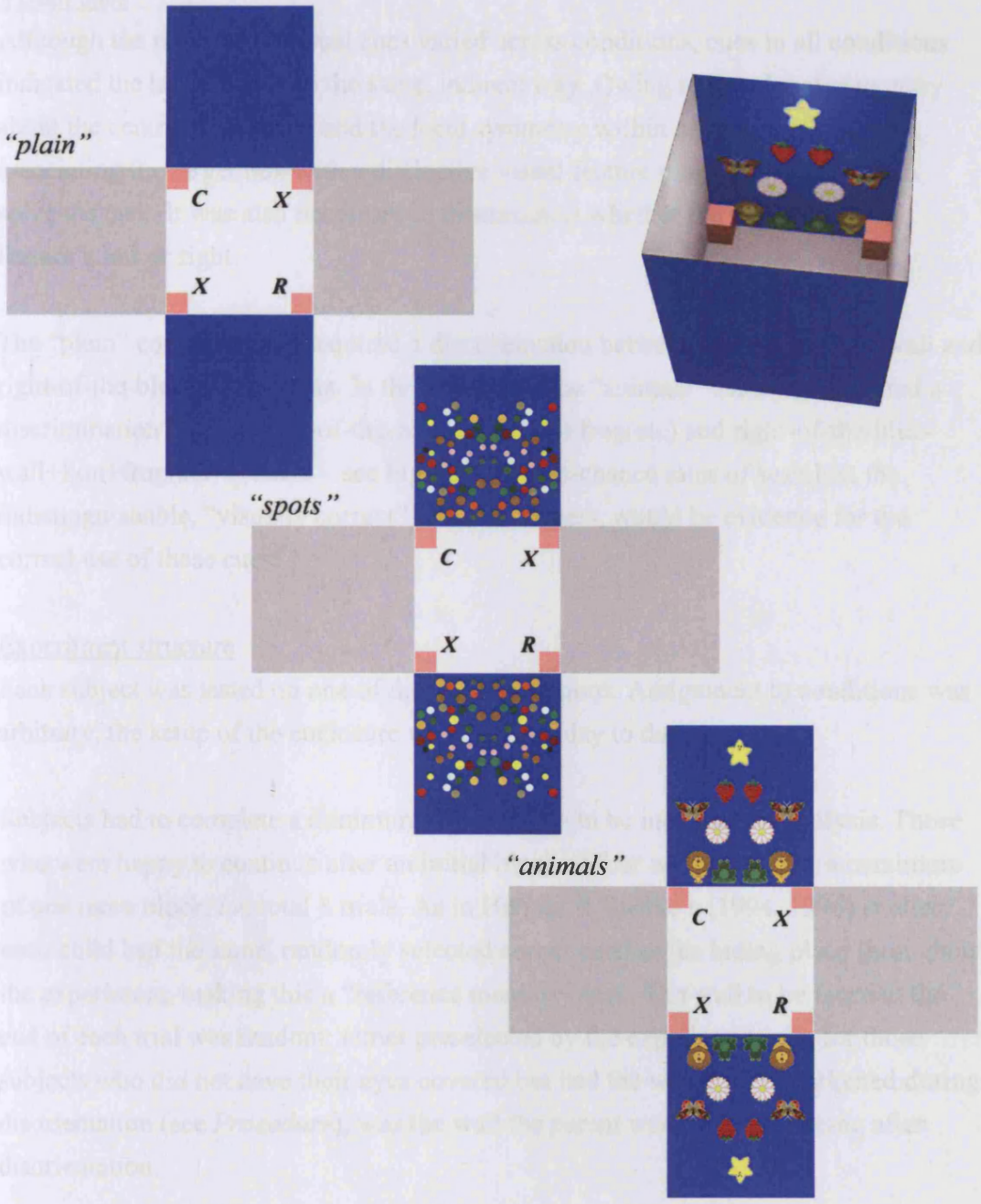


Figure 9. *Schematic layouts for "plain", "spots", and "animals" conditions, and 3D view ("animals" condition). In this example the top left corner is the correct hiding place (C). Adjacent corners X differ in blue-white and animal or spot laterality. The rotationally equivalent corner, R, is visually identical.*

Design

Visual cues

Although the richness of visual cues varied across conditions, cues in all conditions indicated the target boxes in the same, indirect way. Owing to the global symmetry about the centre of the wall, and the local symmetry within each animal and spot, associating the target box with a distinctive visual feature was never sufficient to solve the task. It was also necessary to discriminate whether the box was on the feature's left or right.

The "plain" condition thus required a discrimination between left-of-the-blue-wall and right-of-the-blue-wall corners. In the same way, the "animals" condition required a discrimination between left-of-the-blue-wall+lion+frog(etc) and right-of-the-blue-wall+lion+frog(etc) corners – see Figure 9. Above-chance rates of search at the indistinguishable, "visually correct" C and R corners, would be evidence for the correct use of these cues.

Experiment structure

Each subject was tested on one of the three conditions. Assignment to conditions was arbitrary, the setup of the enclosure varying from day to day.

Subjects had to complete a minimum of four trials to be included for analysis. Those who were happy to continue after an initial block of four were tested for a maximum of one more block, *i.e.* total 8 trials. As in Hermer & Spelke's (1994, 1996) studies, each child had the same, randomly selected corner used as the hiding place throughout the experiment, making this a "reference memory" task. The wall to be faced at the end of each trial was random; either preselected by the experimenter or, for.those subjects who did not have their eyes covered but had the whole room darkened during disorientation (see *Procedure*), was the wall the parent was closest to facing after disorientation.

Procedure

The experiment was conducted jointly by the experimenter and a parent. As in Hermer & Spelke's (1994, 1996) studies, the parent entered the enclosure with the child, while the experimenter gave instructions and observed from outside on a monitor. When they first came into the enclosure, children were allowed to play on the floor with their toy for a minute or two to acclimatise. In conditions with

additional stimuli on the walls ("animals" and "spots"), parents were asked to point these out.

The experiment began once the walls were closed up. On each trial, the parent hid the toy in the box that was in the predetermined corner, ensuring that the child had seen it. Children were encouraged to take an active part, and to help to put the toy in the box. The parent lifted the child and turned her slowly in the centre of the room to induce disorientation. Vision was blocked in one of two ways. Either the parent covered the child's eyes and executed at least four full turns, or the experimenter turned all lights off for 20 seconds while parent and child turned. The lights-off variant was prompted by many children's aversion to having their eyes covered. Neither variant was completely satisfactory, as many children were also averse to being in the dark. Parents tested with the light on were told, before disorientation began, to face a predetermined wall after four turns. Those with the light off faced the centre of whichever wall they saw when the lights came back on.

After disorientation the child was put down in the centre of the room. The parent stood back and encouraged her to find the toy without giving gestural or verbal cues to its location. The experimenter recorded the child's facing direction and the first box searched.

Analysis

Each search was scored C (correct), R (rotational equivalent), or X (neither); see ***Figure 9***Figure 9. Searches were also scored "ahead" (one of the two corners in front of the child), or "behind". Rates of "visually correct" C+R search were compared with chance (50%). The C rate was also compared with the R rate to check that correct search was not due to incomplete disorientation or uncontrolled visual cues. Rates of "ahead" search were compared with chance (50%) to see whether children favoured corners immediately in front of them.

Results

Figure 10 Figure 10 shows numbers of searches at the visual-cue-consistent corners C and R for each condition. The rates of search at these two corners combined (C+R) was greater than chance (50%) in every condition. On binomial tests, numbers of C+R searches were significantly above chance in the "plain" condition ($p < 0.02$) and in the "animals" condition ($p < 0.01$). In the "spots" condition, which had fewer subjects,

the comparison with chance did not reach significance ($p = 0.11$). Considering all three conditions together, a binomial comparison of the number of cue-consistent (C+R) searches with chance was highly significant; $p < 0.001$.

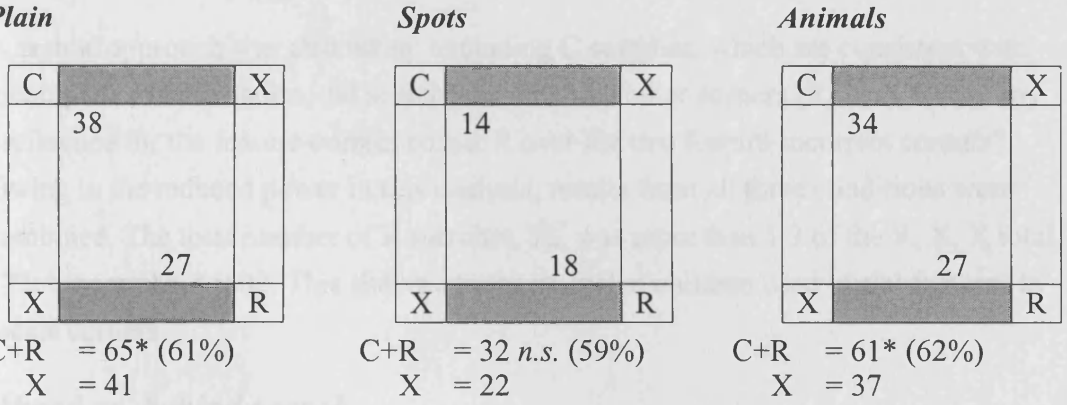


Figure 10. *Number of searches at the correct (C) corner, the visually matching rotationally equivalent (R) corner, and at the visually different X corners. *: rate of visually consistent (C+R) search significantly above than chance (50%) on binomial test; n.s.: not significant.*

These results show that disoriented 18-24 month olds *did* search using indirect "feature" cues in square enclosures, in which room shape ("geometry") indicated all four corners equally. This did not depend on adding visual features to the original design, as the condition with colour only ("plain") also showed the result. The result that disoriented 18-24 month olds were able to use indirect colour to find hidden objects in a small enclosure is novel, and is evidence against the thesis that reorientation at this age depends on a process that is encapsulated with respect to colour (Hermer & Spelke, 1994; 1996).

Across conditions, differences in rates of C+R search were very small (see Figure 9, C+R percentages). The difference was not significant in a 3 x 2 chi square test (condition x type of search; C+R or X); $\chi^2 = 0.13$, $p > 0.9$. The predicted improvement with richer colours, textures and shapes cues was not seen. Rather, as the low χ^2 value shows, performance across conditions was highly consistent.

In the two conditions that showed a statistically significant preference for cue-consistent (C+R) corners, "plain" and "animals", C-searches were slightly more common than those at R. It is important to rule out incomplete disorientation as the

reason for elevated C+R rates. If subjects had no additional cues to the correct corner C, the rate of C search should not be above 50% of the C+R total. Binomial tests confirmed that C rates were not greater than chance for either "plain" ($p > 0.1$) or "animals" ($p > 0.2$) conditions. No test was needed for the "spots" condition in which the R rate was higher.

A second approach was also taken: excluding C searches, which are consistent with incomplete disorientation, did searches at the three other corners (R, X, X) show any preference for the feature-correct corner R over the two feature-incorrect corners? Owing to the reduced power in this analysis, results from all three conditions were combined. The total number of R searches, 72, was more than 1/3 of the R, X, X total, 172; binomial $p < 0.02$. This shows conclusively that children used visual features to locate corners.

Ahead vs. behind search

Whichever way they were facing in the enclosure after disorientation, children would always see a corner that visually matched the hiding place within 180°. Since the two corners in front of the child matched the two behind (see Figure 9), choosing "ahead" *vs.* "behind" corners would not constrain the kinds of searches children could make (C+R *vs.* X). Nevertheless it was asked whether children did tend to search corners that were immediately visible. On the "plain" condition 72 of 106 searches (68%) were straight ahead, a rate significantly greater than chance (binomial $p < 0.001$). On "spots" and "animals" these rates were 34 of 54 (63%; $p < 0.05$) and 57 of 98 (58%; $p = 0.06$). Perhaps the surprising result is the relatively high rates (52% - 42%) at which children decided on corners that were behind them. Although corners in front were favoured - significantly so on two of three conditions – searching straight ahead was clearly not a fundamental principle in children's search. Across conditions, rates of search in front and behind did not differ ($\chi^2 = 2.1$, $p > 0.3$). When all conditions are considered together, 112 of 173 "ahead" searches (64.7%) were visually correct (C or R), while 61 of 95 "behind" searches (64.2%) were visually correct. These very closely matched rates ($\chi^2 = 0.01$, $p > 0.9$) show that choice of ahead and behind was not mediated by the accuracy of memory for the visual features at the corner.

Discussion

The interesting result was that 18-24 month olds *did* search the visually correct C and R corners more often that would be predicted by chance, in two of three conditions, and overall. Discriminating between these and the visually incorrect X corners required laterality judgments: left-of-the-blue-wall (*etc.*) corners had to be distinguished from right-of-the-blue-wall (*etc*). This result is counter to Hermer & Spelke's thesis that such discriminations depend on access to the relevant spatial language terms, not normally acquired until 5-7 years (Hermer-Vazquez *et al.*, 2001).

Use of colour was above chance in the baseline "plain" condition, whose design corresponded to Hermer & Spelke's "four white walls" enclosure, but with the status of colour and geometry cues reversed. In their enclosure, colour indicated all four corners equally while geometry indicated two. Searches above chance at these two corners were evidence for the use of geometry. In this study, geometry indicated all four corners equally while colour indicated two. Searches above chance at these two corners were evidence for the use of colour.

Enriching the colour cues with textures and recognisable shapes did not improve performance significantly. Children's use of colours, textures, and recognisable animals was barely better (62%) than their use of plain coloured walls (61%), suggesting a ceiling in their abilities to use these to reorient. Importantly, the ceiling was below that for children's use of room shape (only): Hermer and Spelke (1996) found that children in the "white room" searched using geometry on 78% of trials. This is consistent with the thesis that geometric cues do indeed have a favoured status for reorientation, and that visual processing of colour and shape is limited in its function at this age. Crucially, however, the present results show that inability to use these is not total, as has previously been claimed.

Children favoured corners straight in front of them to a degree, but this did not account for all their choices of search locations. On a large proportion of searches (52% - 42%) children turned around and searched corners that were behind them, even though these visually match the corners in front. The ahead / behind choice did not interact with recall accuracy, showing that these were independent.

3.3 Experiment 5

The apparent limit on the use of indirect colour and shape for reorientation could be probed further in other ways. One possibility would be to make the blue walls even more salient than in the "animals" condition, perhaps including flashing lights. The present experiment altered the visual cues to ask a different question: is it particularly the left-right laterality of stimuli at the different corners that is difficult to judge, or would colours and features be used relatively little even when the requirement to judge laterality was removed?

For this experiment, the two blue walls had identical but asymmetric displays of animal pictures. Since the animals on the right were different from the animals on the left, the C and R boxes were near a different set of animals than the X boxes. If children's performance did not improve with respect to performance with symmetric stimuli in Experiment 4, this would be further evidence for an in-principle difficulty with recruiting colour and flat shape to drive action at this age – *i.e.*, a hard constraint on how much of this information can ever be processed for action.

Method

Subjects

Subjects were 18-24 month old children recruited from a volunteer database at the Visual Development Unit, University College London. Of 23 tested, 16 completed four or more trials: 8 male, with mean age 21.5, s.d. 1.7 years.

Apparatus

The enclosure was exactly the same as in Experiment 4, except for the flat stimuli fixed to the blue walls. These were animals arranged asymmetrically (Figure 11).

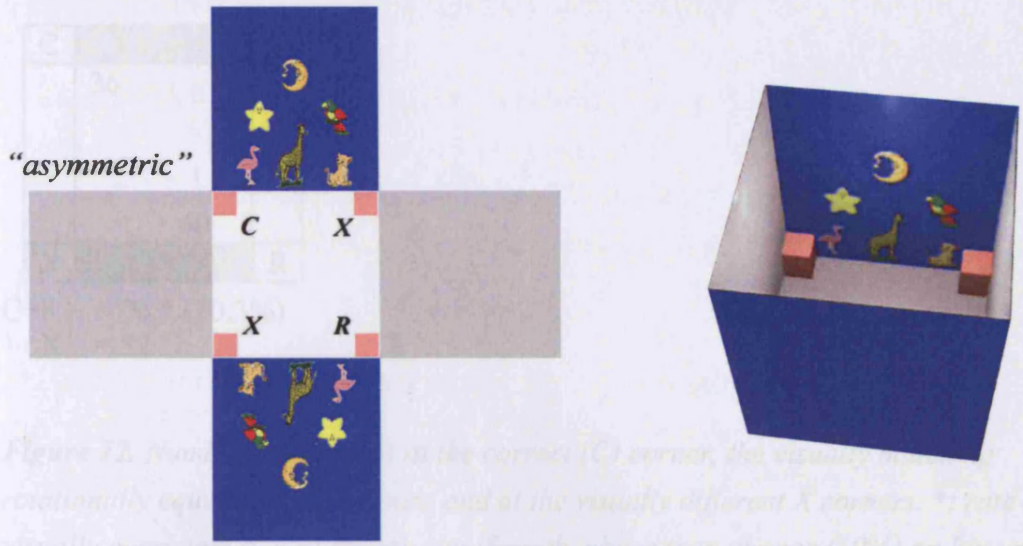


Figure 11. *Layout for the asymmetric condition. Two corners are near the flamingo and the star (in this example, C and R), whereas two are near the lion and the parrot (X). These indirect cues can be used to discriminate C and R from X without a judgment of laterality.*

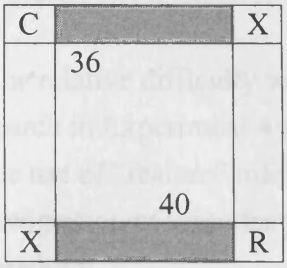
Design, Procedure and Analysis

A judgment of laterality was not necessary to distinguish C+R corners from the X corners (see Figure 11, legend). However corner C was still visually indistinguishable from its rotational equivalent R. Otherwise the design, procedure and analysis were as for Experiment 4.

Results

Figure 12 shows the rates of search at cue-consistent corners C and R. The combined rate of C+R search was 70.3%, considerably above chance (50%), and significantly so on a binomial test ($p < 0.001$). Since the R rate exceeded the C, there is no concern that incomplete disorientation could have produced the high C+R rate.

Asymmetric



C+R = 76 * (70.3%)
X = 32

Figure 12. *Number of searches at the correct (C) corner, the visually matching rotationally equivalent (R) corner, and at the visually different X corners. *: rate of visually consistent (C+R) search significantly above than chance (50%) on binomial test.*

Use of visual cues was better, at 70%, than it had been in conditions that required a laterality judgment (Experiment 4), where rates of C+R search were between 59 and 62%. As performance across the three Experiment 4 conditions did not differ, results from those were combined for comparison with results from the present experiment. The difference between proportions of cue-consistent (C+R) searches was significant on a one-tailed chi square test ($\chi^2 = 2.75$, $p < 0.05$), confirming an advantage for the enclosure with asymmetric stimuli, in which C+R corners could be found without a judgment of laterality.

Ahead vs. behind search

Of 108 searches, 67 (62%) were at "ahead" corners, a rate greater than chance on a binomial test ($p < 0.01$). However rates of visually correct search did not differ for "ahead" and "behind" searches ($\chi^2 = 2.16$, $p > 0.1$).

Discussion

This experiment provided further evidence for disoriented 18 - 24 month olds' ability to search using indirect colours, textures and shapes. With asymmetric stimuli that required no laterality judgment, the rate of feature-consistent search, 70%, was intermediate between the rate of feature-correct search in Experiment 4, where a laterality judgment was needed (59 - 62%) and the rate of geometry-correct search

reported in the white enclosure, 78% (Hermer & Spelke, 1996). These rates should be compared directly in a future study, ideally within subjects.

The relative difficulty with which 18 – 24 month olds used flat coloured landmarks to search in Experiment 4 therefore cannot be accounted for entirely by a limitation on the use of "feature" information for search. The difficulty diminished when recognition of these features did not need to be combined with a judgment of laterality.

In Hermer and Spelke's previous studies the cue provided by room shape was quite easily combined with laterality. That is, it was quite easy to discriminate left-of-the-long-wall from right-of-the-long-wall. By contrast in Experiment 4 it was quite difficult to discriminate left-of-the-blue-wall (*etc*). from right-of-the-blue-wall (*etc*) – although these discriminations were still at rates reliably better than chance.

These results suggest an interesting disjunction in the way that the shape of the room and the flat landmarks on its walls might be processed in this task. It seems that compared with symmetrically arranged walls, symmetrically arranged colourful "features" are more subject to be confused with their mirror opposite. That is, children are more likely to confuse two mirror images of a flat coloured landmark than of a corner of the room.

3.4 Experiments 4 – 5, General Discussion

These results show that at 18 - 24 months, disoriented children can use coloured walls to search for hidden objects, contrary to the "geometric module" thesis which holds colour to be inaccessible by the reorientation mechanism. However comparison with previous results suggests that geometric cues are nevertheless favoured for reorientation. Geometric left-right judgments are relatively easy. Colour left-right judgments are relatively difficult, irrespective of added textures and shapes. Colour and shape judgments without the need to make left-right discriminations are still quite difficult.

The result that colourful "feature" cues *can* be used to reorient at this age supports the thesis that children's inability to use colour in the original task stems from a difficulty with combining different kinds of visual information, rather than with attending to wall colours in the first place.

Findings such as that the disregard of colour effect is abolished in larger enclosures (Learmonth *et al.*, 2001, Learmonth *et al.*, 2002) suggest that the original "blue wall" phenomenon may obtain only under highly specific circumstances. However it does not follow from this that it must depend on a dedicated process (the "geometric module"). It would be more parsimonious if the effect could be explained by general principles of visuocognitive development. The question is whether similar effects can be found in other tasks with a different structure – for example, in memory tasks that do not involve reorientation. If "disregard of colour" were found to be a more pervasive phenomenon in early visul cognition, this would extend the "blue wall" effect but undermine the claim that it depends on a specialised module which only operates under disorientation.

Further studies and a new hypothesis

Further studies should examine whether the "blue wall" phenomenon can be understood in terms of existing models of visual information processing. They should also include an independent measure of children's ability to use colour alone to remember locations. This is necessary to rule out the possibility that children simply did not attend to colours in the first place.

One way to understand the dominance of room shape over colour in the "blue wall" task could be as an "action / perception" dissociation. Room shape constrains a participant's actions, because movement must be planned with respect to the shape of the room. By contrast, the colours of its wall do not constrain how a participant is able to move. This could place these two categories of cue on opposite sides of a proposed divide between visual pathways involved in perception (visual recognition) on the one hand, and action (visuomotor planning) on the other (Ungeleider & Mishkin, 1982; Goodale & Milner, 1992; Milner & Goodale, 1995).

There is evidence for a functional dissociation between the ventral visual stream, subserving recognition, and the dorsal stream, providing spatial information for the control of action (Milner & Goodale, 1995). Recent challenges to Milner and Goodale's formulation suggest that a "planning / control" divide exists within the parietal "action" system; Glover, 2004). Despite these disagreements, these formulations share a proposed functional and anatomical distinction between an inferotemporal system dedicated to "recognition", and a system for "action" (including planning), though the latter is conceived in different ways.

To solve the "blue wall" disorientation task it is necessary to combine the geometric cue that can guide action with the colour cue that characterises a recognisable object. It may be that the geometric cue predominates because it is processed by the dorsal stream, and that children's failure to use the colour cue reflects an immaturity in combining information provided by the two visual pathways.

"Action / perception" dissociations are normally studied in table-top tasks in which participants reach towards objects. The framework therefore may or may not be applicable to codings of the local environment, although an imaging study found a dorsal / ventral separation for codings of location and landmark identity in a virtual space (Aguirre & D'Esposito, 1997). The thesis of early functional separation of the streams has support (Mareschal & Johnson, 2003; DeLoache, Uttal, & Rosengren, 2004), though studies of colour and motion integration suggest that for some kinds of visual information, functional separation is preceded by a period in which there is greater cross-talk between the systems than in adulthood (Dobkins, 2005). It would however be relatively straightforward to test whether 18-24 month olds' disregard of wall colour can be understood as a more pervasive feature of early visual cognition, linked to the need to integrate visual information for action with information for recognition. To test for the generality of the effect, these tasks should not involve disorientation.

One kind of desktop task could present children with four boxes, each with a toy hiding/retrieval mechanism. The manner of retrieval would differ for pairs of boxes – two could require pressing a button, whereas the other two could require pulling a string. At the same time colours of the boxes, but not the retrieval mechanism itself, would differ such that two colours were present and served to disambiguate the boxes. One "button" box could be blue and the other white, similarly one "string" box could be blue and the other white. In other words, the 2x2 design, mechanism x colour, would make the boxes ambiguous to anyone attending only to retrieval action or only to colour, but would disambiguate them for a participant who integrated action and colour information.

The experiment would be run as similarly as possible to the "blue wall", but on a desktop and with no disorientation. In the interval between hiding and retrieval, the positions of the boxes would be shuffled around.

The prediction is that 18-24 month olds would favour the action over the colour. To confirm the specificity of such an effect, it should be compared with baseline measures for other bindings in the box task (*e.g.*, flat shape with colour). An older,

transitional age range should also be tested on both this task and the classic "blue wall" reorientation task. The prediction is that performance on the two would correlate better than would performance on either task with that on a third memory task without a "dorsal-ventral" binding component.

CHAPTER 4

The development of spatial frames of reference

4.1 Introduction

The "blue wall" studies examined how two categories of visual cue, environment shape and colour, are used and combined under disorientation. Disorientation eliminated body-referenced representations of the layout. Retrieval therefore depended on using a combination of visual cues to find the object. In this task the processing of different visual cues (colour, shape) could be distinguished. However the relative contributions of body- and environment-referenced representations were hard to separate. For example, it remained an open question whether subjects retrieved the object by first re-establishing their own orientation within the enclosure and then using an egocentric vector, or whether they could have remembered its location allocentrically (with respect to the landmark provided by the blue wall).

The following set of studies used a different kind of search task to separate and compare body-referenced and environment-referenced representations, and to ask how these might be combined. The interest was not in the category of visual cue that is used, but in what frame of reference is used to remember a spatial relation. The approach in these studies was to vary the participant's viewpoint with respect to a hidden object. When there is no change of viewpoint, purely egocentric representations as well as representations using landmarks can be used. When there is a change of viewpoint before retrieval, purely egocentric representations cannot be used, and retrieval must depend either on landmarks or on body-referenced representations that have been updated by self-motion (*i.e.*, using path integration).

"Landmark" and "spatial updating" solutions to viewpoint-change problems can also be distinguished. When a change of viewpoint is produced by self-motion, both landmarks and spatial updating are available. However if the change of viewpoint is not accompanied by self motion (if the array of hiding places is moved while participants stays still), no self-motion information is available, and retrieval can only be based on landmarks. Developmental tasks described in the introduction (Chapter 1) used some of these subject- and array-displacement manipulations (*e.g.* Bremner & Bryant, 1977; Acredolo, 1978; Newcombe *et al.*, 1998), but none did so in a way so systematic and confound-free that a clear conclusion about the development of different spatial frames of reference could be drawn. The aims of the following set of studies were to develop a test that discriminates between different spatial representations, to characterise the development of and interactions between these, and to test hypotheses about their neural basis with clinical groups.

4.2 Experiment 6

An initial approach was to adapt a virtual reality test of same-viewpoint and different-viewpoint recall developed by King and colleagues (King *et al.*, 2002). On this test, the participant sees a large outdoor scene, a "town square" presented on a computer screen. One or more objects appear in sequence in the middle of the square. After a short interval, the participant judges where the objects were, either from the same viewpoint within the virtual space, or after being moved to a new viewpoint. From the new viewpoint, recall cannot be based on the egocentric frame of reference defined by the body, or that defined by the computer screen, but must be based on visual cues within the virtual environment. A patient with bilateral hippocampal pathology was impaired specifically on the shifted-viewpoint conditions (King *et al.*, 2002). Therefore as well as offering an easy way of showing and manipulating objects in an otherwise difficult to obtain large-scale space, the test already had an established neural correlate. It only needed to be made easier for children, by including fewer possible hiding places, and a smaller number of objects to remember on each trial.

Individuals with Williams Syndrome have great difficulties with visuospatial tasks (Bellugi *et al.*, 1988; Atkinson *et al.*, 2001). Some parents of individuals with WS who have visited the Visual Development Unit report that their children have trouble finding their way around, which would be consistent with their visuospatial deficits. One hypothesis would be that their impairments include a difficulty with allocentric representations involving landmarks. Therefore the adapted "town square" task was also evaluated as a test for children and young adults with Williams Syndrome, in whom it could potentially identify a specific deficit for viewpoint-independent recall based on landmarks.

Method

Subjects

Subjects were six typically developing children aged 7-12 years (mean age 9.7, s.d. 1.9 years), eight children with Williams Syndrome aged 8 – 15 years (mean age 11.7, s.d. 2.6 years), and five young adults with Williams Syndrome aged 19 – 23 years (mean age 21.5, s.d. 1.0 years).

Apparatus

The experiment was presented on a 19" monitor with resolution 1280x1024. The virtual environment was implemented using an adaptation of the game Quake 2 (ID

Software) originally programmed by King and colleagues (King *et al.*, 2002) and adapted further here to make the task simpler. A joystick was used to move around the virtual space. The environment is illustrated below (*Procedure*, Figure 13).

Design

The experiment had a 2x2 design with the factors viewpoint at recall (same or shifted by 135°), and number of objects to remember (one or two). There were six trials in each condition. All the one-object trials were presented first. These came in four blocks of three, with the viewpoint factor (same or shifted) changing between blocks. The two-object trials were presented next, the viewpoint factor likewise alternating every block of three.

In the presentation phase, subjects saw either one object, or two different objects in sequence, appear in the "town square". In the test phase, subjects saw the same object, from the same viewpoint or from a viewpoint shifted by 135°, as well as two identical objects (foils) at two other (incorrect) locations. The task was to determine which of the three was in the same place as the original object. On two-object trials recall for the two objects was tested in sequence. On half of these the sequence was opposite to the sequence in which the objects were originally presented. For both presentation and test, the places where objects might appear were constrained to ten locations within the town square, each marked by a red "stone". The objects that appeared were pictures of animals, which varied from block to block. Hiding locations and locations for each of the foils were pre-selected randomly, but each subject experienced the same randomly generated sequence.

The probability of selecting a correct object by chance on any trial was 1 / 3. The overall proportion of objects expected to be found by chance on each of the four conditions was likewise 1 / 3. Although the two-object conditions included twice as many objects to remember, the same proportion of these as of the one-object trial objects would be found by random search; the two-object conditions were however more demanding in that both objects needed to be held in memory at the same time.

Procedure

Subjects either moved themselves around the virtual space using the joystick, or watched as the experimenter moved them around. Some younger control children, and most subjects with Williams Syndrome, were not competent at controlling their own movement. All subjects had the different features of the virtual environment pointed

out on them. The task was explained on two one-object practice trials, one each of the same-viewpoint and different-viewpoint conditions. The layout of the virtual space and the procedure for the subsequent trials is explained in Figure 13.

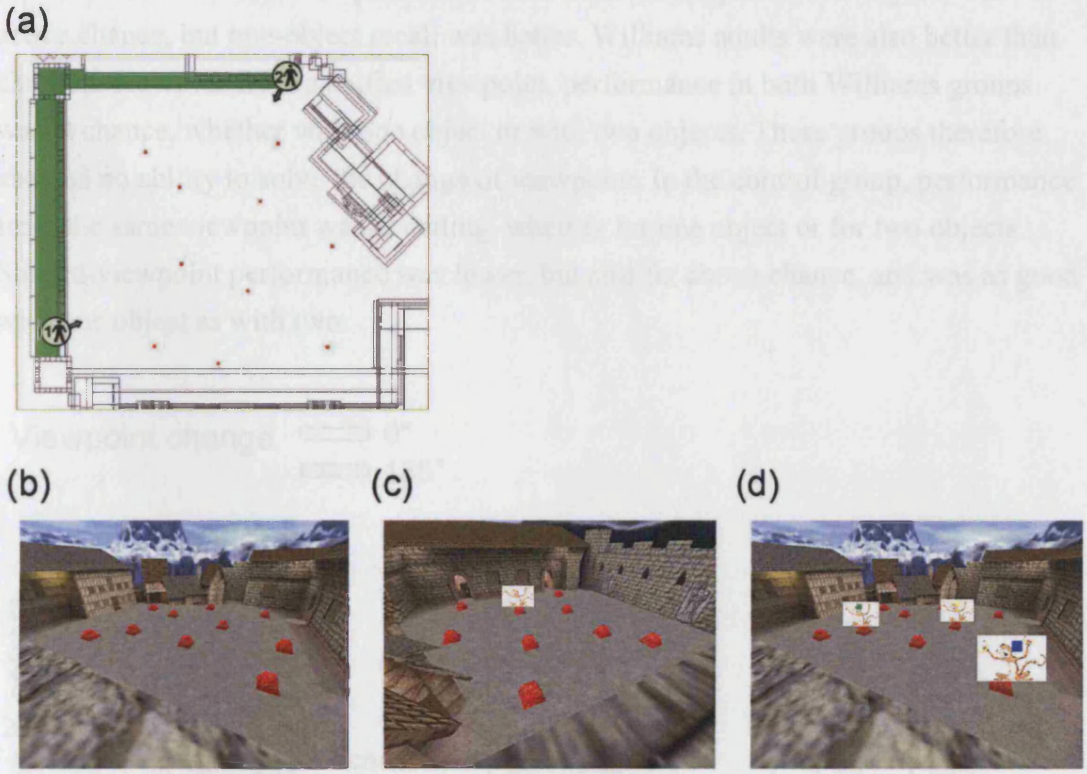


Figure 13. *Layout and procedure. (**a**) illustrates the environment from above (but was not seen by subjects), while (**b-d**) show example views within the virtual space. Subjects were on a high walkway above the "town square" (**a**, green) throughout. They started each trial at position "**1**" (**a**), with view (**b**) of the space. They walked to position "**2**" (**a**), where they saw view (**c**), initially with no object. From this viewpoint, either one object, or two objects in sequence appeared in the town square. In (**c**) a monkey has appeared. After a pause of 5 seconds, subjects either reappeared back at the start - a viewpoint change of 135°, illustrated in (**d**) – or remained in the same place – a viewpoint change of 0°, not shown. The object (one-object trials) or one of the objects (two-object trials) reappeared in the same place, along with identical foils in two other places. These three were distinguished by different colours. Subjects were asked which object was in the same place as the one they saw before, and responded either by pointing or by naming the colour. On two-object trials, the other object was then presented in the same way.*

Results

Mean percentages of correct answers by group and condition are plotted in Figure 14. Performance in both child and adult Williams Syndrome groups followed a similar pattern. From the same viewpoint, recall for either one object or two objects was above chance, but one-object recall was better. Williams adults were also better than children. However from a shifted viewpoint, performance in both Williams groups was at chance, whether with one object or with two objects. These groups therefore showed no ability to solve the change of viewpoint. In the control group, performance from the same viewpoint was at ceiling, whether for one object or for two objects. Shifted-viewpoint performance was lower, but still far above chance, and was as good with one object as with two.

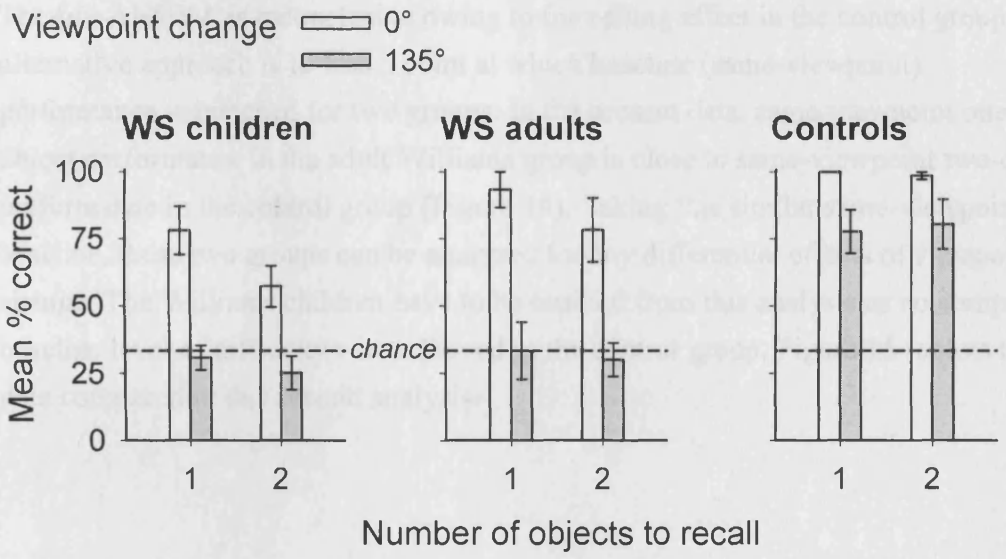


Figure 14. Mean percent correct trials (standard error bars) by group and condition. White bars: recall from the same viewpoint. Grey bars: recall from a viewpoint shifted by 135°. Bars on the left: recall for a single object. Bars on the right: recall for two objects. The chance level of performance, 33%, is indicated.

The three groups were compared in an ANOVA with between-subjects factor *group* and within-subjects factors *view change* and *objects*. There was a main effect of *group* ($F(2) = 23.6$, $p < 0.001$), a main effect of *view* ($F(1, 16) = 55.6$, $p < 0.001$), and a smaller main effect of *objects* ($F(1, 15) = 4.9$, $p < 0.05$). These results show that performance differed between groups, and that both experimental manipulations had effects on performance.

The *group* x *view* interaction approached significance ($F(2,16)=3.8$, $p=0.06$). This marginal effect corresponds to a stronger effect of a change of viewpoint for the Williams groups than for the control group (see Figure 14Figure 14). However, the ceiling performance in the control group from the same view means that the range of measurement is reduced. Therefore the difference between same-viewpoint and different-viewpoint performance in the control group is likely to be an underestimate.

The *group* x *objects* interaction was not significant ($p>0.2$): all groups tended to show lower performance with two objects (Figure 14; although one- and two-object performance in the control group was practically indistinguishable). Finally, neither *view* x *objects* ($p>0.1$) nor the three-way *view* x *group* x *objects* interaction ($p>0.8$) were significant.

The full ANOVA is inconclusive owing to the ceiling effect in the control group. An alternative approach is to find a point at which baseline (same-viewpoint) performance is matched for two groups. In the present data, same-viewpoint one-object performance in the adult Williams group is close to same-viewpoint two-object performance in the control group (Figure 14). Taking this similar same-viewpoint baseline, these two groups can be analysed for any differential effects of viewpoint change. The Williams children have to be omitted from this analysis as no comparable baseline level of difficulty was achieved in the control group. Figure 15 replots the data compared in this second analysis.

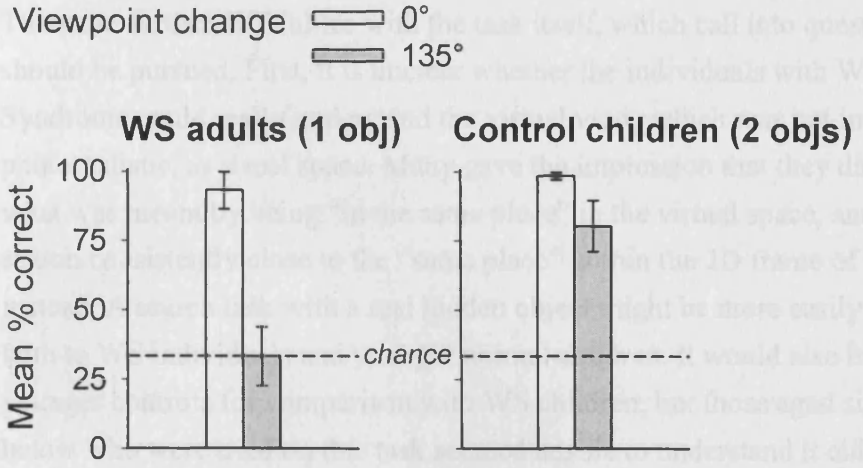


Figure 15. *Mean percent correct trials (standard error bars) from groups and conditions with a comparable same-viewpoint baseline. White bars: recall from the same viewpoint. Grey bars: recall from a viewpoint shifted by 135°.*

Mean baseline (same-viewpoint) performance for these two groups was similar (93.3% *vs.* 98.6%), and did not differ significantly ($t(9) = 0.85$, $p > 0.4$). An ANOVA found a main effect of *group* ($F(1) = 10.2$, $p < 0.02$), a main effect of *view* ($F(1,9) = 30.0$, $p < 0.001$), and a *view* x *group* interaction ($F(1,9) = 8.6$, $p < 0.02$). This interaction indicates that adults with Williams Syndrome were differentially impaired on same-viewpoint and different-viewpoint recall with respect to younger controls. It is true that the baseline match may still be inaccurate, as both groups are close to measurement ceiling.

Discussion

These initial results give some support to the hypothesis that individuals with Williams Syndrome have a specific difficulty with viewpoint-independent recall based on visual landmarks. The results however are inconclusive, and this should be thought of as a pilot study. The main difficulty was obtaining a range of performance without floor or ceiling effects. With WS individuals, the two-object conditions were uninformative as shifted-viewpoint recall was already at floor (chance) with one object. With controls, both one- and two-object same-viewpoint recall was close to ceiling. WS subjects should ideally be tested with one object only, while controls should be tested with a range of objects (2 and above) in order to match same-viewpoint performance. The control group was also small, and not matched to the Williams groups on any measure (*e.g.* verbal age).

There are further difficulties with the task itself, which call into question whether it should be pursued. First, it is unclear whether the individuals with Williams Syndrome could really understand the virtual view, which was not immersive or photorealistic, as a real space. Many gave the impression that they did not understand what was meant by being "in the same place" in the virtual space, and some seemed to search consistently close to the "same place" within the 2D frame of the screen instead. A search task with a real hidden object might be more easily comprehensible both to WS individuals and younger normal children. It would also be ideal to test younger controls for comparison with WS children, but those aged six years and below who were tried on this task seemed unable to understand it either. A further difficulty is that the measure, percent correct (with a 1 / 3 probability of being correct by chance), is not sensitive given the small numbers of trials that can be used with children. A more sensitive measure would be based on allowing participants a free choice of search location on every trial, and taking a metric (distance) measure of error.

4.3 Experiment 7

In this study the virtual environment was exchanged for a real testing space with hidden objects. Despite the flexibility and convenience of using the virtual space, it seemed not to be suitable for typically developing children aged six years or less, nor for many individuals with Williams Syndrome. A real environment also made it possible to separate and test a wider range of representations in spatial memory. In particular, the displacement cue provided by self-motion, not available for virtual changes of viewpoint, could now be assessed.

This test was a development of the "town square" (King *et al.*, 2002), and retained some of the features of that task. As before, landmarks on two sides bordered a set of possible hiding places. Subjects experienced two viewpoints of the array, which were 135° apart. Other elements of the design were adapted from adult studies by Simons and Wang (Simons & Wang, 1998; Wang & Simons, 1999). In particular, the manipulations of viewpoint were done across four conditions rather than two. These conditions, detailed below, enabled a comparison of viewpoint-changes produced by self-motion with passive viewpoint changes, like those in the virtual town square. Finally, unlike either the "town square" or the Simons and Wang task, the score from each trial was not correct or incorrect, but a metric measure of error, *i.e.* distance from the correct place. This kind of accuracy measure, previously used by Newcombe and

colleagues (Newcombe *et al.*, 1998), would be more sensitive given a small number of trials.

The adult array rotation studies of Simons and Wang (Simons & Wang, 1998; Wang & Simons, 1999), mentioned in Chapter 1, should first be described in full. These studies provided an elegant demonstration of the parallel effects of frames of reference defined by (i) the body, and (ii) the surrounding environment in the following way. Participants were shown an array of five objects and subsequently asked to say which of the objects had been moved. Between presentation and test, the participant's position and the array's orientation within the room were manipulated so that the array of objects remained either consistent or inconsistent with its initial position, as judged relative to (i) the body and (ii) the room. In the baseline condition, where both frames of reference were available, participants were tested from the same place in the room and the array did not move. When they moved to a new place in the room, and therefore saw a new view of the array, the body-array relation was made inconsistent. The room-array relation was made inconsistent when participants moved to a new place, but the array was simultaneously rotated so that their view of it matched the view seen at the start. Finally, when the array was rotated but participants answered from the same place in the room, both relations were made inconsistent. Simons and Wang's results showed that the frames of reference provided by body and environment had additive effects on recall accuracy. Recall was most accurate when both were consistent between presentation and test, and least accurate when neither was consistent. These manipulations of observer position and array orientation provide the basis for the present developmental study.

The first result from Simons and Wang's work was improved performance when the array did not move within the surrounding room. For example, participants who moved to a new viewing position performed better than those who experienced the equivalent viewpoint change when it was produced by rotation of the array. In an illuminated testing room, two different effects could explain this advantage. First, accuracy could be improved by allocentric representations of the objects' locations within the surrounding framework of visual cues. Array rotation would disrupt these relationships. Second, participants who walked to a new position had the advantage of self-motion cues, including those from the vestibular sense and from motor-efference, to the distance and direction of their displacement. These cues could be used for "internal updating" of the object locations.

Spatial updating processes are found in many species, including humans (Mittelstaedt & Mittelstaedt, 1980; Loomis *et al.*, 1993; Farrell & Robertson, 1998). Simons and

Wang (1998) argued that spatial updating was sufficient to explain the room-consistency effect, since it was still found in a darkened room, where no landmarks external to the array were visible. In a subsequent study, Burgess, Spiers, & Paleologou (2004) separated effects of spatial updating from use of an allocentric reference frame by additionally varying the array's consistency with an external landmark. They found performance advantages both for consistency with movement cues and for consistency with the landmark, showing that subjects used both spatial updating from self-motion cues and allocentric representations of location relative to an external landmark.

The second result from Simons and Wang's work was an advantage for consistency with the body: participants were more accurate when they viewed the array from the same angle at presentation and test. The availability of a familiar view would make it possible to recall the layout using egocentric representations such as stored visual images. Advantages for recall from familiar viewpoints are reported in species ranging from ants to humans (Judd & Collett, 1998; Diwadkar & McNamara, 1997; Roskos-Ewoldsen, McNamara, Shelton, & Carr, 1998). The Simons and Wang paradigm is innovative in allowing the comparison of body-consistency and room-consistency effects within the same task.

A final result was that when none of the frames of reference provided by body or environment were consistent between presentation and test, accuracy was still far above chance. In this condition, produced by rotating the array while keeping the participant in the same place in the room, the only frame of reference that remained consistent was provided by the array itself. This type of allocentric frame of reference, also referred to as an *intrinsic* reference frame (Levinson, 2003), was defined by the array's layout and overall shape. An allocentric representation providing a viewpoint-independent map of the array's layout would account for participants' ability to solve the task. Alternatively, participants could mentally rotate the array and match it to a stored visual image. The task does not distinguish between these possibilities, but common to both is the requirement to adopt a frame of reference intrinsic to the array, distinct from those defined by the observer or the testing space.

To summarise, the array rotation paradigm provides measures of a range of different representations in spatial memory. In this study, developmental data was collected using a modified version of the task. It is worth noting how the task relates to the classic literature on viewpoint-independence reviewed in Chapter 1 (Piaget & Inhelder, 1967; Huttenlocher & Presson, 1973). In those studies, children imagined taking a different perspective with respect to a spatial layout and used models or

diagrams to indicate what they would see. These tasks were interesting because they required participants to retrieve layouts in a viewpoint-independent manner, *e.g.* using allocentric representations. They proved difficult, and were not solved until around 10 years. However the additional demands of these tasks make it likely that this did not only reflect difficulties with forming viewpoint-independent representations. The present task offers a more direct assessment of viewpoint-independent recall, in the form of object search. The test for viewpoint independence is the condition in which neither body nor room frames of reference are consistent between presentation and test, and only visual cues within the spatial array can be used.

The Simons and Wang design also avoids two difficulties with related developmental search tasks by Huttenlocher, Newcombe and colleagues (Huttenlocher, Newcombe, & Sandberg, 1994; Newcombe *et al.*, 1998), described in Chapter 1. In those studies the viewpoint-change condition entailed an additional walking task, which children who answered from the same place did not have. Children were also apparently not prevented from refixating the hiding place and tracking it while walking around the array. In the adult task of Simons and Wang the walking demand was matched across conditions, so that participants responding from the same position walked the same distance between presentation and test as those responding from the other position; to do this, they walked halfway to the other position and back. Fixation of the array during the interval was not possible because it was only viewable at the two test positions.

The present study adopted these features of the array rotation paradigm, as well as its factorial design. Instead of a change detection task, which might not be so easily comprehensible to children, or older individuals with a disorder such as Williams Syndrome, it took the form of a search task with hidden toys. On each trial the child had to recall the position of a single toy hidden in one of 12 identical containers bordered by distinctive landmarks, from the same or from a different position, after rotation or no rotation of the whole array, including these local landmarks. All participants experienced all conditions.

Viewpoint-independent retrieval could depend on something other than allocentric spatial representations. One possibility is that it depends on the ability to form verbal representations of the hiding places. A final trial on which a verbal description of the hiding place was elicited, without warning and when the array was not visible, measured the extent to which children's representations of the hiding places were verbally mediated.

A pilot study determined a suitable age range. It was clear that children much younger than those testable in the virtual environment understood the task. The lower limit was reached at around three years. Those aged two pursued a strategy of simply lifting or knocking over containers until they found the toy. They could not be made to understand that they should indicate a single cup and wait to see whether their guess was correct. Children aged three years and above however understood the procedure and enjoyed the task.

Method

Subjects

Participants were children at London primary schools and nurseries, and volunteers at the Department of Psychology, University College London. The total tested was 73 children: 18 three year olds (mean age 3.5, *s.d.* 0.25 years; 9 male), 21 four year olds (mean age 4.5, *s.d.* 0.26 years; 11 male), 17 five year olds (mean age 5.5, *s.d.* 0.30 years; 8 male) and 17 six year olds (mean age 6.5, *s.d.* 0.35 years; 9 male). The mean ages of males and females did not differ overall ($p>0.9$), nor did they differ within any age group (for all groups, $p>0.4$).

Apparatus

The test apparatus (Figure 16 a) comprised a dark green board measuring 82 cm x 82 cm. A portion of the board (70 cm x 70 cm) was taken up by an array of 12 identical inverted white cups (diameter 8 cm) arranged in a fixed pattern, which avoided the appearance of a grid or other distinctive figure. Toy houses and animals, which could serve as landmarks were arranged in the remaining, space, occupying two of the board's edges. More distant uncontrolled visual cues, which were fixed and therefore could not provide a basis for retrieval when the array was rotated, were also present in the testing room. Two viewing positions were marked on the floor, 20 cm from two adjacent edges of the board. The line of sight of each was 22.5° from the normal to the nearest edge. The view of the array was therefore shifted by 135° between the two positions. A line which participants walked between hiding and retrieval was also marked on the floor. The stimuli whose hiding places had to be recalled were small attractive toys.

Design

Subject movement and array rotation varied according to a 2x2 design with the factors *body consistency* and *room consistency*. Before retrieval, children either walked to the other viewing position, or halfway and back to their initial position. At the same time, the array was either rotated by 135° relative to the room, or was not rotated. When the

child walked around and the array rotated, the hiding place remained consistent with the body – that is, the original view of the array was matched. The conditions in the experiment are described in detail in **Figure 16**Figure 16 a and b. Note that the two factors state the hiding place's consistency with *body* and *room* respectively, but neither states the participant's absolute position in the testing room. In this respect the present description of the 2x2 design differs from that in Wang and Simons (1999), although it embodies the same four conditions. The frame of reference defined by the *array* itself was always consistent between presentation and test. In the *array-move* condition this provided the only basis for correct retrieval.

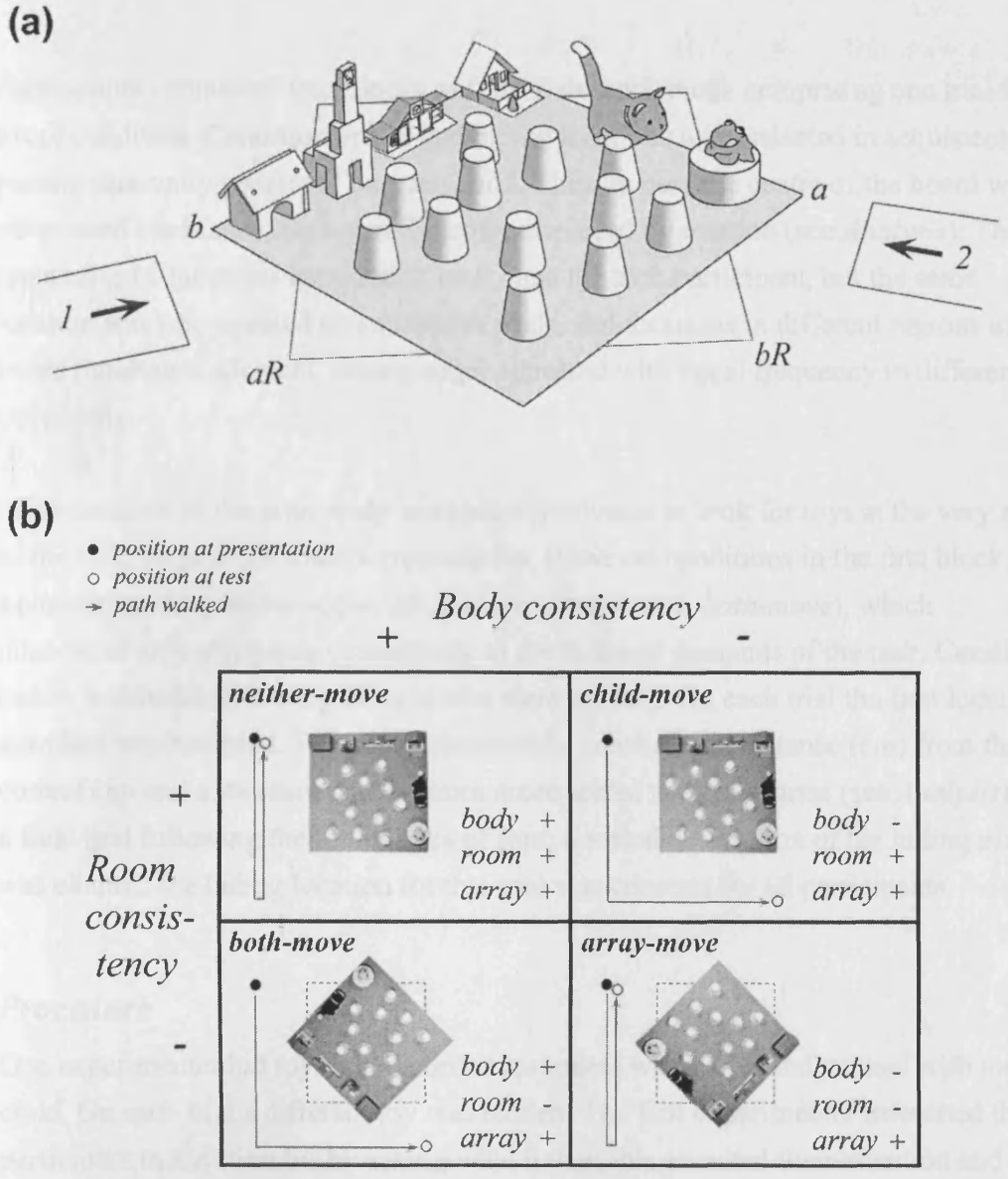


Figure 16. *The apparatus (**a**). After the toy was hidden, changes in the hiding place's relation to the body (i.e., changes in the angle at which participants viewed the array) were obtained either by walking the child to a new position (child-move condition; e.g., walk from 1 to 2), or by rotating the board (array-move condition; e.g., board rotates a to aR while participant walks from 1 halfway to 2, and back to 1). When participant position changed and the board rotated (both-move condition), the original body relation (viewing angle) was matched (e.g., subject walks 1 to 2 while board rotates b to bR). In the baseline neither-move condition, the child walked halfway to the other position and back and the board was not rotated. These four conditions (**b**) systematically varied the hiding place's consistency with the body and the room. The frame of reference provided by the array itself was always consistent between presentation and test. This frame of reference provided the only basis for correct retrieval in the array-move condition.*

Participants completed four blocks of four trials, each block comprising one trial from every condition. Condition orders and hiding locations were selected in sequences pseudo-randomly generated for each child. The cup near the centre of the board was never used because it was not sufficiently displaced by rotation (see *Analysis*). The remaining 11 locations appeared at least once for each participant, but the same location was not repeated on successive trials, and locations in different regions of the board (landmark-adjacent, centre, edge) appeared with equal frequency in different conditions.

Since children in the pilot study were most motivated to look for toys at the very start of the task, no practice trials were included. However conditions in the first block had a constant order (*neither-move, child-move, array-move, both-move*), which introduced all participants consistently to the different demands of the task. Condition orders within the following three blocks were random. On each trial the first location searched was recorded. This was subsequently converted to distance (cm) from the correct cup and a standard performance score scaled against chance (see *Analysis*). On a final trial following the four blocks of four, a verbal description of the hiding place was elicited; the hiding location for this trial was constant for all participants.

Procedure

One experimenter hid toys and recorded responses while a second walked with the child. On each trial a different toy was hidden. The first experimenter interested the participant in the stimulus by asking what it was: this attracted their attention and helped to establish interaction with shy children. Identification of the toy (*e.g.* a teddy, a pig, a dinosaur) met with enthusiasm from the experimenters, who praised success generously in order to counteract the potentially demotivating effect of failing to find the toys.

The first experimenter picked up one of the cups and set the toy down in the space under it. While the cup was still held in the air, the experimenters checked that the participant was attending to the position of the toy by asking a question, for example "can you see where he's hiding?". The cup was lowered once the experimenters were sure that the child had seen the toy. The second experimenter then walked the participant either all the way around to the other viewing position, or halfway and back. A large sheet of card was held to one side of the child's face to block their view of the array during the entire walking phase. Both experimenters monitored the child's gaze, and those who tried to look past the card were warned not to "peek" and

encouraged to look up at the experimenter who was walking with them instead. On the *room inconsistent* conditions (*both-move* and *array-move*) the first experimenter additionally rotated the board during this part of the trial.

In the search phase both experimenters directed their gaze at the participant rather than at any part of the array. Children were asked to use a ruler to tap the top of the cup where the toy was hiding, and an experimenter lifted the cup. By preventing children from lifting cups by themselves, a process hard to regulate once allowed to get underway, we emphasised the importance of recalling the right cup rather than using trial and error.

On the first occasion when rotation occurred, the experimenters carefully demonstrated how the board could be turned before the trial began. On all rotation trials, children were warned before they searched that the array had "turned around". These measures were motivated by the finding in the pilot study that younger children tended to search as if the rotation had not occurred. It was important to counter the possibility that any child was unaware that a manipulation of the board had taken place. On all trials other than the first rotation trial, children did not know where they would be walking, and whether the array would be rotated or not, until the toy had been hidden and the walking phase had started. Each trial began at whichever viewing position the last had ended. The even distribution of same position and different position trials meant that on average the two viewpoints were experienced equally often.

On a final trial the toy was always hidden under the same cup. This location admits a variety of correct verbal descriptions, but is uniquely specified by its relation to two landmarks, "between the cat and the frog" (see **Figure 16**Figure 16 a). Participants were not given advance warning that this trial would differ from the others. However after the toy was hidden, the second experimenter turned the child away from the array and, blocking their view with the card, asked: "can you *tell* me where [the toy] is hiding?" For children who did not answer or tried to point, the question was repeated in different ways ("can you *say* to me where it is?"). Answers were recorded verbatim.

Analysis

The dependent measure, first cup searched, was initially converted to a distance (cm) from the correct cup, 0 cm indicating a correct search. For each trial this error distance was transformed into a standardised performance score as follows. Each hiding place

has an associated average error expected by chance. This value, which would be obtained by a participant searching at random over many trials, is given by the mean of the distances between that place and all 12 possible search locations, including the correct one, and varies from location to location[1]. Performance scores were calculated with the formula *100 * (chance distance –error distance) / chance distance.* The effect of this transformation is that 100 corresponds to a correct search, while 0 corresponds to a search at a distance equal to chance. A value below 0 corresponds to a search error greater than the average expected by chance.

A participant's overall performance score for each condition was calculated as the mean of their scores in that condition. Each participant thus contributed four mean performance scores, one for each condition, to this part of the analysis. A repeated measures ANOVA was carried out with within-subjects factors *body consistency* and *room consistency* (see **Figure 16**Figure 16 b), and between-subjects factors *age group* and *gender.*

The analysis described so far measures performance on each trial as a distance between correct location and chance. However the correct location is not the only place at which it might be hypothesised that searches will consistently occur. In fact, on three of the conditions, the use of a frame of reference incorrect for the condition would predict a search at a specific incorrect location. An example of this is provided by younger children in the pilot study, who searched, in the *array-move* condition, close to the place where the toy had been before board rotation took place. This indicates either ignorance of the manipulation, which this study has sought to rule out (see *Procedure*), or an incorrect choice of frames of reference. In this condition, the frames of reference defined by *body* and *room* both specify the same, incorrect location (see **Figure 16**Figure 16 b).

Accordingly in the *array-move* condition, the place specified by these frames of reference, which corresponds to the place occupied by the toy before rotation, was taken as the origin for a second calculation of "performance score". Since no cup precisely occupies the place of another following rotation, it is not possible to obtain a score of 100 (search error 0 cm) on this measure. Nevertheless it can be determined whether searches at any age were closer to the hypothesised place than would be expected by chance.

[1] The values range from 23.1 cm to 33.8 cm, with mean 29.0 cm (*s.d.* 3.7cm).

Similarly, in the *both-move* condition, a second hypothesised location for search was the place correct with respect to a frame of reference defined by the *room*, *i.e.* the toy's initial place before rotation. A search at this location would suggest that this frame of reference was used in preference to those defined by *body* and *array*. In the *child-move* condition, a possible second location for search was the place initially correct with respect to the *body*. Searching close to here would constitute the classic "egocentric" error seen in very young children, who search after movement as if they have not moved (*e.g.* Acredolo, 1978). Since the children in this study were much older than those reported to make the egocentric error, this pattern was not anticipated.

The relationship between each "alternative hypothesis" performance measure and the main performance measure is such that a score above chance on one usually equates to a score below chance on the other. This is a function of the magnitude of the view difference, 135°, which displaces cups (apart from the unused centre location) considerably from their original positions. There is a strong negative correlation between the main performance measure and the alternative performance measure; *e.g.*, for all combinations of hiding and search locations on the *array-move* condition, r=-0.46.

A further analysis was more exploratory. It would be interesting to see whether some locations were better remembered than others. An ANOVA was carried out on performance scores from all trials, with the factors *location* (1-11), *body consistency*, and *room consistency*. Since the total number of trials per location was limited, these data were not suitable for further subdivision by age or gender. Neither was the experiment designed to balance the many possible factors influencing ease of recall. Even so, variations in performance as a function of hiding place would potentially be of interest.

A final analysis examined answers on the unexpected verbal trial. The logic of the test was this: a child who was mentally rehearsing a phrase would most likely produce the phrase in response to the question. On the other hand, a child who was not using a verbal strategy could likewise produce the phrase by describing a mental image. In other words, the use of a verbal strategy was a sufficient but not a necessary condition for a correct verbal description. Failure to describe the location could therefore be taken as good evidence for the absence of a verbal strategy, but success would be equivocal.

Results

Mean performance scores by age group are plotted in **Figure 17**Figure 17 a. The same order of condition difficulty (*neither-move, child-move, both-move, array-move*) is evident at every age, and matches the pattern of adult performance on the change detection task of Wang and Simons (**Figure 17**Figure 17 b). This pattern is consistent with the decreasing availability of different frames of reference across conditions (see Figure 16 b): *neither-move* (body + room + array) > *child-move* (room + array) > *both-move* (body + array) > *array-move* (array). The 95% confidence intervals show that mean performance on *both-move* was not significantly above chance until four years, while performance on *array-move* was not above chance until five years. Groups of children aged five and six years were therefore above chance at recalling from a novel viewpoint a location indicated only by spatial relations intrinsic to the array, *i.e.* the relative positions of landmarks and cups.

There were main within-subjects effects for *body consistency* ($F(1, 65)=31.1$, $p<0.001$) and *room consistency* ($F(1, 65)=159.8$, $p<0.001$), but there was no interaction between these factors ($p>0.9$). The between-subjects factor *age* was significant ($F(3)=24.3$, $p<0.001$); there was a significant interaction between *age* and *room consistency* ($F(3, 65)=12.2$, $p<0.001$), but no interaction between *age* and *body consistency* ($p>0.6$). The three-way interaction between *age, body* and *room consistency* was not significant ($p>0.1$).

These results show that performance was improved by consistency with both the frames of reference provided by the body and the environment. These two factors did not interact, but were additive. The effect of consistency with the *room* changed significantly over the age range (significant interaction *room consistency* x *age*), while the effect of consistency with the *body* did not (no significant interaction *body consistency* x *age*). These results are evident in Figure 17 a: the difference between bars on the left (*room* consistent) and bars on the right (*room* inconsistent) reduced with age. At the same time, the difference between white (*body* consistent) and grey (*body* inconsistent) bars was quite constant across ages. It is striking that the effect of *room consistency* was much greater than the effect of *body consistency* for the youngest children. The absence of a significant three-way interaction between *body* and *room consistency* and *age* reflects the regularity with which the *body* and *room* factors combined in all age groups.

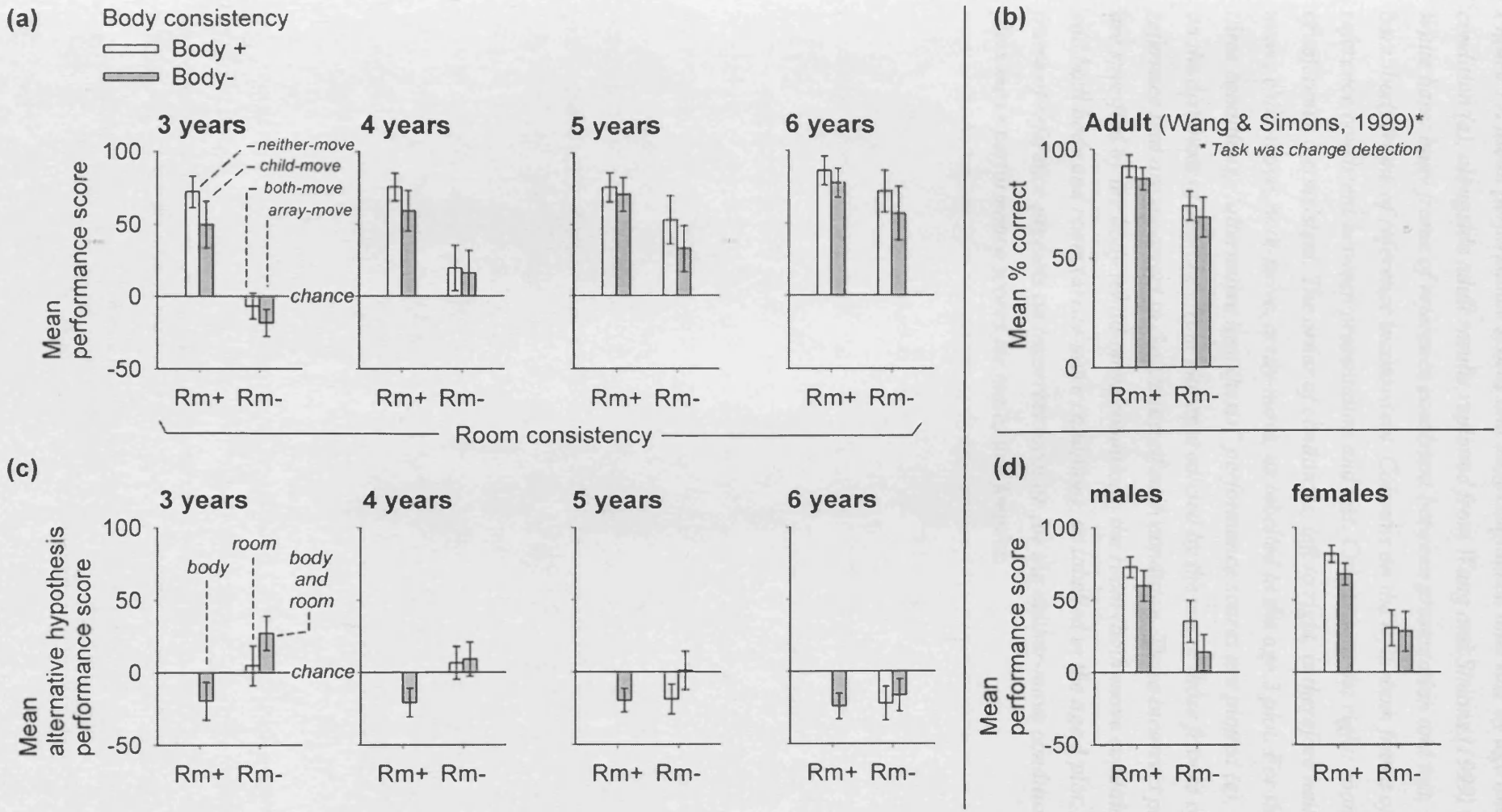

(a)
Body consistency
Body +
Body-
3 years
4 years
5 years
6 years
neither-move
child-move
both-move
array-move
chance
Mean performance score
100
50
0
-50
Rm+ Rm-
Room consistency
(b)
Adult (Wang & Simons, 1999)*
* Task was change detection
Mean % correct
(c)
body
room
body and room
Mean alternative hypothesis performance score
(d)
males
females

Figure 17. *Mean performance scores and 95% confidence intervals by age and condition (**a**), alongside adult results replotted from Wang and Simons (1999) (**b**). White bars: body frame of reference consistent between presentation and test. Grey bars: body frame of reference inconsistent. Columns on the left: room frame of reference consistent between presentation and test. Columns on the right: room frame of reference inconsistent. The order of conditions, left to right, is therefore neither-move, child-move, both-move, array-move, as labelled in the age 3 plot. For the latter three conditions, "alternative hypothesis" performance scores are plotted (**c**), based on the distances of searches from places predicted by the use of those frames of reference that are incorrect in the context of each condition. These incorrect places are specified by the body (child-move condition), the room (both-move condition), and both body and room (array-move condition), as labelled in the age 3 plot. No frame of reference predicts an incorrect location for the neither-move condition. (**d**) plots mean performance scores for males and females.*

The 95% confidence interval for the *array-move* condition at age 3 shows that performance was significantly *below* chance. That is, three year olds searched further from the correct location than would participants searching at random, which implies the consistent use of an incorrect strategy. The alternative hypothesis measure for this condition predicted searches close to the place initially correct with respect to both *body* and *room*. The proximity of searches to this location, compared with the distance expected by chance is plotted in **Figure 17**Figure 17 c. For the *array-move* condition (grey column on the right) at age 3, searches were significantly closer to this place than chance. Thus when faced with a rotation of the array and a novel view of it, three year olds' searches were consistent with the frames of reference provided by *body* and *room*, whereas correct retrieval would entail disregarding these and using only the frame of reference intrinsic to the *array*. The mean proximity of search to this incorrect location fell steadily with age, and was not above chance for any age group above 3. Searches on the *both-move* condition were not significantly closer than chance to the location predicted by the incorrect use of a *room* frame of reference at any age (**Figure 17**Figure 17 c, white column on the right).

When the board did not rotate, the *room* frame of reference specified the correct location for search. The *child-move* condition replicates previous tests of retrieval after walking to a new viewpoint (e.g. Newcombe *et al.*, 1998). Performance on this condition improved with age (**Figure 17**Figure 17 a, grey bars on the left). To determine whether the improvement was significant, mean *child-move* performance scores were analysed in a one-way ANOVA with the factor *age*. The effect of *age* was significant ($F(3)=3.64$, $p<0.02$). Thus between 3 and 6 years, accuracy improved on the classic task of retrieving a hidden object after walking to a novel viewpoint. The alternative search location predicted for the *child-move* condition was the place initially correct with respect to the *body*. In every age group, searches were significantly further from this place than chance (Figure 17 c, grey column on the left). This confirms that even the youngest group in the study did not make the classic "egocentric" error on this condition, but took their change of position into account when they searched.

Performance on the baseline *neither-move* condition (Figure 17 a, white column on the left) showed a small, nonsignificant improvement with age ($F(3)=1.47$, $p>0.2$). Since mean scores were not close to measurement ceiling (score 100), this does not seem to be the limiting factor. Rather, with all frames of reference available, recall for a single object among 12 locations was already good at 3 years, but those limitations of accuracy (and perhaps continuous attention to the task) which kept it below ceiling were still in place at age six.

Effects of gender

The between-subjects factor *gender* was not significant alone ($p>0.1$), but only in a three-way interaction with *body consistency* and *room consistency* ($F(1, 65)=4.8$, $p<0.05$). This interaction is plotted in Figure 17 d. Females were better on all conditions except *both-move*, and showed a particularly large advantage on the *array-move* condition. Males were much less accurate on *array-move* than on *both-move*, whereas females' performance on these conditions was similar. Although females were (nonsignificantly) better overall, it is interesting that the *gender* interaction does not simply imply a faster overall development for the females.

Performance by hiding location

An ANOVA with factors *location*, *body consistency* and *room consistency* found a main effect of *location* ($F(10)=2.2$, $p<0.02$), an interaction between *location* and *room consistency* ($F(10)=2.1$, $p<0.03$), but no interaction between *location* and *body consistency* ($p>0.3$), and no three-way interaction between these factors ($p>0.2$). **Figure 18**Figure 18 plots mean performance scores as a function of hiding location and *room consistency*. The interaction is evident mainly in that choice of hiding location had greater effects on performance when the *room* frame of reference was inconsistent.

In both room consistent and inconsistent conditions, the places recalled with least accuracy were near the centre of the array and far from any landmarks. Immediate proximity to a landmark was helpful, but not necessary for a high rate of correct retrieval: the corner cup (bottom right, Figure 18) was well remembered, particularly in the room inconsistent conditions. The corner of the board may have served as a landmark, but it is also likely that this cup's distinctive position in the layout of the array made it memorable. It is also true that positions at the edge of the array have fewer nearby alternatives than those in the middle.

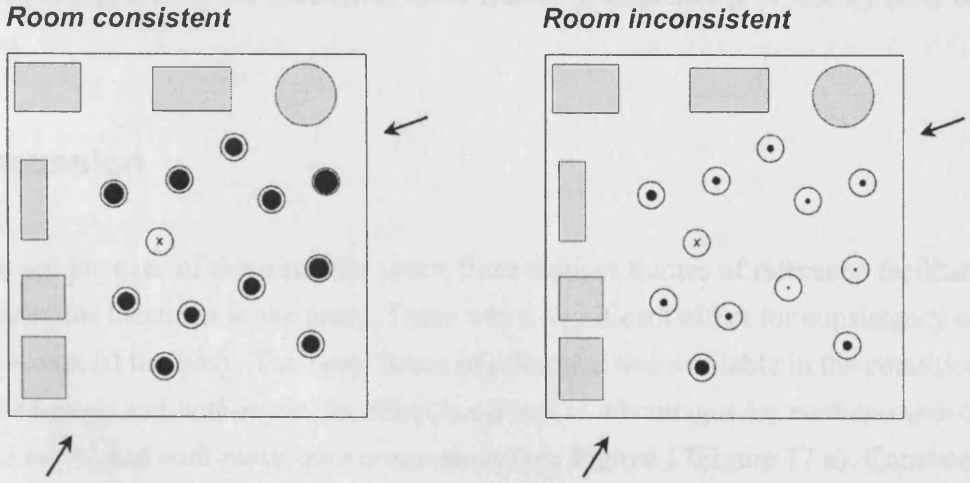


Figure 18. *Mean performance scores by location on room consistent conditions (left) and room inconsistent conditions (right). The array is shown from above, with landmarks (grey), cups (white circles), and the two viewing angles (arrows). Diameters of black circles correspond to mean performance scores. The scale ranges from no black circle (mean score 0), to the edge of the cup (mean score 100). "x" marks the central cup, which was never used.*

Verbal descriptions

Only three children, all aged six, mentioned both the cat and the frog in response to the surprise question on the final trial. Descriptions mentioning either landmark were more common - examples included "near the cat", "beside the cat", "next to the frog". Although these might not suffice to describe the location unambiguously to a third party (see **Figure 16**Figure 16 a), they could be a basis for retrieval in a participant who understood them in a particular way. Answers that referred to either landmark were therefore scored as correct descriptions. There were no correct descriptions at age 3, four at age 4, five at age 5, and 12 at age 6. As percentages of children in each age group, these were 0%, 19%, 29%, and 71%. Other children tended either to give no response, or to give nonspecific answers ("over there"; "in the cup").

To check whether the emergence of viewpoint-independent recall at five years could have depended on verbal encodings, performance on the *array-move* condition was examined for only those five year olds who did not mention either landmark in response to the surprise question (n=12; mean age 5.4 years, s.d. 0.27). The performance of these children was above chance at the 5% level (mean score 21.9 with 95% c.i. 2.5 – 41.3, which excludes 0). Thus even those five year olds who could

not produce a verbal representation of this hiding place demonstrated viewpoint-independent recall in the absence of those frames of reference provided by *body* or *room*.

Discussion

Between the ages of three and six years, three distinct frames of reference facilitated memory for locations in the array. There was a significant effect for consistency of the target with (i) the *body*. The *body* frame of reference was available in the conditions *neither-move* and *both-move*. Its effect is evident in advantages for *neither-move* over *child-move*, and *both-move* over *array-move* (see **Figure 17**Figure 17 a). Consistency with the *body* would allow the use of egocentric representations that are not updated with movement, such as stored visual images. Those representations that facilitated performance when the *body* relation was held constant were already developed by three years, and did not undergo significant changes through age six.

There was a further effect for consistency with (ii) the *room*. The *room* frame of reference was available in the conditions *neither-move* and *child-move*, and its effect can be seen in advantages for *neither-move* over *both-move*, and *child-move* over *array-move* (Figure 17 a). Like the *body* effect, the *room* effect was already present at three years. The striking result was that at this early age, it was much greater than the *body* effect (see Figure 17 a, and F values above): the array's position within the external reference frame of the room influenced the youngest subjects much more than its position within the egocentric reference frame defined by the body. This large *room consistent* advantage in performance in the youngest children must have depended on representations that are not purely egocentric – *i.e.*, those taking external space into account, whether through landmark use or spatial updating This result shows that any spatial "egocentrism" in infancy had definitively disappeared by three years, at which age children showed a strong awareness of their movement within the surroundings. When the toy's position within the room was changed, but purely egocentric retrieval remained possible because the body relation was kept constant (*both-move* condition), performance at three years was at chance, whereas in a young "egocentric" infant good performance would be expected from a comparable condition. The *room* effect diminished over the age range (as performance in the room-inconsistent *array-move* and *both-move* conditions improved), but was still present at age six. An ANOVA with only those children aged six confirms that the effects of both *body* and *room* were significant at this age.

The factors (i) *body* and (ii) *room consistency* did not interact, showing that when both frames of reference were present their effects were additive. The order of condition difficulty in every age group, which was consistent with the availability of these frames of reference, matched the pattern found in adults on a similar task (Wang & Simons, 1999). The consistency with which this additive pattern occurred across the age range meant that there was no significant three-way interaction between these two factors and *age*.

Performance on the conditions *both-move* and *array-move*, which were not consistent with the *room*, (Figure 17 a, bars on the right), steadily caught up with performance on the conditions that were consistent (bars on the left). This age trend was the result of two separate effects. First, when neither of the frames of reference provided by *body* or *room* indicated the correct location (*array-move* condition), the youngest children nevertheless searched consistently with these (Figure 17 c). As a result their performance was very low; indeed at three years searches were further from the correct places than would be expected by chance. However performance on this condition rose significantly above chance at five years. Simply ignoring those frames of reference that were incorrect for this condition would have sufficed to bring performance to, but not beyond, chance. To perform above chance, the five and six year old groups must have used some further frame of reference to solve the task. The only frame of reference that remained stable with respect to the target in the *array-move* condition was provided by (iii) the array itself, *i.e.* an "intrinsic" frame of reference (Levinson, 2003). Children aged five and six years must have developed the ability to retrieve objects using only those visual cues present in the array. These included the landmarks around two of its edges, as well as the edges themselves and the configuration of hiding places (cups).

Developmental changes in the use of the *room* frame of reference therefore reflected its replacement by the more appropriate *array* frame of reference in older children. For this reason, these results do not indicate whether or how much the *room* frame of reference became used more effectively with age. It is striking however that use of the *room* frame of reference was already present at three years, and that it was so privileged over the *body* frame of reference at this young age.

The emergence of viewpoint-independent retrieval at five years in this present study was much earlier than reported in the classic perspective-taking studies of Piaget & Inhelder (1967) and Huttenlocher & Presson (1973), where the transitional age was around ten. The present results are consistent with Newcombe & Huttenlocher (1992), who found greatly improved performance when responses were directed at the spatial

array itself, rather than at a diagram. In their study, three year olds were above chance at indicating, from an (imaginary) novel viewpoint, the positions of objects which did not move within the room between presentation and test (allowing use of a *room* frame of reference), and whose places within the array were constant throughout (allowing children to learn the places incrementally over the course of the experiment). In this study, five year olds were above chance at retrieving locations that moved with respect to both body and room between presentation and test, and that changed from trial to trial. These results provide evidence for viewpoint-independent retrieval based only on spatial relations intrinsic to the array at five years.

Children in this study were not instructed to solve the task by imagining a perspective change. It has been argued that imaginary perspective changes are difficult because they entail a conflict between the participant's real position and the imaginary position. However in the present task, the condition that tested for viewpoint independence (*array-move*) included an analogous conflict. Children had to inhibit responses based on the frames of reference provided by *body* and *room*, and there was evidence in the youngest children's errors for a failure to do this. An inhibition process may therefore be an additional component of the task. It should therefore be taken as a conservative indicator of the emergence of viewpoint-independent retrieval of intrinsic spatial relations, which may be present even earlier than measured here.

What might explain the emergence of viewpoint independent recall at five years? It could be explained by verbal representations, imaginary rotation, or allocentric ("intrinsic") representations of the hidden toys' places within the array. The surprise question showed that those five year olds who could not produce a verbal description of the hiding place were still above chance at viewpoint-independent recall. There was therefore no evidence that viewpoint-independent recall depended on verbal representations. This conclusion is based on a cautious criterion for identifying possible verbal strategies, which was biased towards detecting "false positives". The location was one of those most easy to describe, the question was asked at the end, which allowed time for any strategy to develop, and descriptions were scored "correct" on a generous criterion. A reanalysis confirmed viewpoint-independent recall when all five year olds who gave such a description were excluded, even though these descriptions could have been provided by children who were describing mental images, and not pursuing a verbal strategy.

The other two possibilities are less easy to distinguish from these measures. One account is that children adopted the strategies, explicitly required in Piaget's and Huttenlocher's tasks, of mentally translating the current view of the array into a

different one. On the alternative account, children developed the capacity to represent locations with respect to the landmarks and other visual features within the array. That is, they encoded locations on an internal "map" of the array, which enabled them to retrieve these directly from novel viewpoints. A result that bears on this question is the effect of hiding location (Figure 18). The interaction between *location* and *room consistency* corresponds to greater differences across locations on the *room* inconsistent conditions, including the condition *array-move* which provides the test for viewpoint-independent recall. On these conditions, locations that were neither close to a landmark, nor at a distinctive place in the array's shape were recalled with least accuracy (Figure 18, right). This pattern is consistent with an encoding process that represents array locations with respect to local landmarks and overall shape. The same pattern would not obviously be predicted by mental rotation. If mental rotation did take place, then it is surprising that locations at the array's edges, which would have to travel furthest, were subject to less error than those near its centre. This pattern gives some reason to favour the hypothesis that viewpoint independent recall in these children corresponded to an emerging ability to represent locations with respect to local visual cues, but this conclusion remains tentative. Some kind of piecemeal mental rotation using landmarks as local anchor points would represent a compromise between these accounts, and would be consistent with the data.

It has been hypothesised that children used direct retrieval from intrinsic (array referenced) representations on the present task, whereas mental rotation was one of the requirements that made the classic perspective change studies difficult. These arguments make a testable prediction, which is that if compared on the same task, children given a free choice of strategy would perform better than those instructed to use imaginary perspective changes. If retrieval depended on imaginary perspective changes, the opposite pattern would be expected, an immediate clue to the correct solution conferring an advantage on the "perspective change instruction" group.

Consistency with *body* and *room* had different effects on males and females aged 3 to 6. Females outperformed males on every condition but *both-move* (Figure 17 d). Their performance on this condition and on *array-move* was very similar, whereas males' performance on *array-move* was much poorer. Females in this age range were therefore better at using an array centred frame of reference, needed to solve the *array-move* condition, but showed little improvement resulting from additional consistency with the *body* in the condition *both-move*. The female advantage on the baseline (*neither-move*) condition is consistent with results from adult change detection without a change of viewpoint (McBurney, Gaulin, Devineni, & Adams, 1997). Interestingly gender differences for the other conditions differed from those in

a comparable adult array rotation task (Burgess *et al.*, 2004), where a significant interaction with gender again corresponded to an overall advantage for females, but this (adult) female advantage included the *both-move* condition but not the *participant-move* condition. The pattern giving rise to a significant interaction in the current study was opposite for two of these conditions: three to six year old females performed better than males on *child-move*, but less well on *both-move*. These differences suggest that rates of development for the use of different frames of reference differ for males and females. Such developmental differences across the age range studied here did not produce any significant interactions involving *gender* and *age*, although the four-way interaction between *gender, age*, *body*, and *room consistency* approached significance ($p=0.07$). The trends evident in this interaction were consistent with differential rates of development eventually giving rise to the adult pattern.

The *child-move* condition corresponds to a standard test of recall from a novel viewpoint. Although performance was already good at three years, it continued to improve significantly through age six. By contrast, the baseline same viewpoint (*neither-move*) condition showed small improvements which did not reach significance. Since mean scores did not reach measurement ceiling, this effect seems to represent a genuine performance ceiling for this age range. This could indicate attentional or motivational limitations, adding to the data a degree of noise, which is relatively constant for ages three to six years.

The apparent emergence of viewpoint independence at a later developmental stage in previous related tasks (Piaget & Inhelder, 1967; Huttenlocher & Presson, 1973) may have been partly due to their additional requirement for taking the perspective of another being. An important result from this study was that children as young as three years showed no evidence of the spatial "egocentrism" reported in very early childhood, but were strongly influenced by the hidden object's place within the environment. The early presence of distinct representations taking into account body and environment, and the additive effects of these, consistent across the age range, indicate a continuum with adult performance (Wang & Simons, 1999). The mechanisms that underlie these representations are likely to be shared in young children, adults, and potentially other species.

Neural correlates

A final issue to consider are possible neural correlates for the frames of reference and representations identified and behaviourally characterised in this task. Based on the

adult and animal literature (Chapter 1), there are possible correlates for all the main findings from this study; namely, the early awareness of hiding places' relation to both body and room at three years, the initial dominance of the room, and the emergence of purely viewpoint-independent recall at age five.

The early-developing *body* advantage implies "purely egocentric" representations, *i.e.* those not updated by self-motion. "Purely egocentric" responses in very young children are often identified with motor plans, dependent on the dorsal visual stream and posterior parietal cortex (Milner & Goodale, 1995). The early use of the *room* in the present task however suggests that any such motor plans were not purely egocentric, but were updated by self-motion even at the youngest ages. More likely candidates for "purely egocentric" representations are stored visual scenes, dependent on the ventral visual stream and inferotemporal cortex (Milner & Goodale, 1995). Adult imaging and neurorecording indicates viewpoint-dependent representations of visual scenes specifically in parahippocampal cortex (Epstein *et al.*, 2003; Ekstrom *et al.*, 2003).

The similarly early-developing and initially stronger *room* advantage may depend on posterior parietal representations that are body-referenced, but updated by self-motion (Bremmer, Duhamel, Ben Hamed, & Graf, 1997; Colby, 1999). The initial dominance of these over egocentric representations such as visual scenes could represent an early bias for dorsal-stream over ventral-stream representations of space (Rosetti, 1998). Interestingly, early perceptual processing in the lower levels of the dorsal and ventral streams shows no such ventral-stream advantage; indeed ventral-stream judgments mature more rapidly (Braddick, Atkinson, & Wattam-Bell, 2003). Therefore if the early dominance of the *room* frame of reference does reflect a preference for dorsal-stream representations, this may depend on a subsequent selection process (or differential timing in the two pathways) rather than the processing capabilities of the dorsal and ventral streams themselves. These alternatives may not be possible to distinguish using purely behavioural measures, but could in future be tested using neurorecording methods, e.g. ERP. The strong *room* effect is also consistent with early use of visual landmarks external to the array. An adult array rotation study which distinguished landmark use from spatial updating by moving an external landmark relative to the participant (Burgess *et al.*, 2004) found effects for both, but in the present task these cannot be dissociated since they predict the same behaviour. It is likely however that room landmarks did contribute to the *room* advantage, as previous studies indicate external landmark use at ages even younger than those tested here (*e.g.* at 22 months; Newcombe *et al.*, 1998). Landmark use is associated with the hippocampus, where damage impairs memory for locations defined by distant visual

landmarks in humans (King *et al.*, 2002) and rats (Morris, Garrud, Rawlins, & O'Keefe, 1982; Pico, Gerbrandt, Pondel, & Ivy, 1985), and neurons directly reflect memory for locations relative to landmarks in rats (*e.g.* Lenck-Santini, Muller, Save, & Poucet, 2002; O'Keefe & Speakman, 1987) and humans (Ekstrom *et al.*, 2003).

The final result was children's emerging ability, at five years, for viewpoint-independent recall using only the *array* frame of reference. As noted above, viewpoint-independent representations of locations relative to landmarks are associated with the hippocampus, which appears to be able to simultaneously support separate representations referenced to local and to room landmarks (Zinyuk, Kubik, Kaminsky *et al.*, 2000). A second component of the ability to use only the *array* frame of reference may be inhibition of the incorrect *body* and *room* frames. Competence on inhibition tasks is considered to depend on the development of the frontal lobes (Goldman-Rakic, 1987; Diamond, 1990a).

In conclusion, the *body* frame of reference probably depends on inferior temporal representations of visual scenes, while the *room* frame of reference may depend on egocentric representations that are spatially updated by self-motion (dependent on dorsal stream and posterior parietal cortex), as well as allocentric representations of location relative to landmarks within the room (dependent on the hippocampus). The present results suggest that these processes were already present and well developed at three years. The later emergence of viewpoint-independent recall using only visual cues within the array implies intrinsic representations of the array, which may depend on further hippocampal and prefrontal development.

4.4 Experiment 8

It is clear from the six year old data in the previous study that the age range for this task could not be extended much higher without reaching ceiling (see **Figure 17**Figure 17 a). Adults informally tested on the task tended to achieve perfect performance on all conditions. An interesting question is to what extent these later developmental improvements reflect further refinements in spatial representations, and to what extent they represent the switch to a verbal strategy. 71% of six year olds gave answers consistent with use of a verbal strategy, and all adults who were asked to attempt the task reported that they used words.

This apparent switch to a verbal strategy in older subjects makes it difficult to assess what improvements, if any, occur in nonverbal spatial representations of angle and

distance. It is conceivable that such representations are in fact more or less mature around age five. Alternatively, it could be that spatial representations continue to improve in accuracy in later childhood, but cannot be measured on a task of this kind since subjects choose to use words, which they find more accurate still (or perhaps easier).

The following short study verified the ceiling effect and the spontaneous choice of a verbal strategy in a group of adults, and assessed performance in a second group who were deprived of verbal representations by a verbal interference task. The interesting question was how adults deprived of verbal representations would compare with children in the previous study. Since subjects tested with verbal interference have to carry out an additional task, a parity between verbally occupied adults and children doing the task normally would be inconclusive. However superior performance in verbally occupied adults, despite the attentional *etc.* demands of the interference task, would be good evidence for further development of nonverbal spatial representations beyond six years.

Method

Subjects

The adult subjects were 27 undergraduates at University College London. After testing under either verbal shadowing or non-shadowing conditions, subjects were assigned to a "verbal" or "non-verbal" group for analysis, based on whether they reported using words to remember the locations (see *Procedure*). All non-shadowing plus one shadowing subject were "verbal" (n=15, 7 male; mean age 21.7, s.d. 3.1 years). The remaining shadowing subjects were "non-verbal" (n=12, 4 male; mean age 20.2, s.d. 1.6 years).

These were compared with the five and six year olds from Experiment 7, as well as three seven year olds who were too old to be included in that analysis. These children were categorised on the basis of their response to the unexpected final verbal trial. Those giving a correct description of the final hiding place were classed "verbal" (n=19, 11 male; mean age 6.4, s.d. 0.5 years), the rest "non-verbal" (n=18, 8 male; mean age 5.7, s.d. 0.7 years). Note that the "verbal" category is likely to be over-inclusive, as it would include any children who were not pursuing a verbal strategy but were able to describe a mental image.

Apparatus and Design

The testing array and toys were those used in Experiment 7. Adults in the shadowing group heard a shadowing stimulus of newspaper articles being slowly read out (the same stimulus used in Chapter 2, Experiments 1 - 3). Headphones were used to play either these articles, or, for non-shadowing subjects, white noise. The design and order of conditions were the same as in Experiment 7.

Procedure

For adults, the procedure from Experiment 7 was modified in two ways. First, a second experimenter did not help adults walk around. Instead, they were shown lines on the floor to walk along, and lines on the walls to fixate while walking (to prevent them from watching the array). On each trial, adults walked by themselves either around to the other position or halfway and back, following a hand signal from the experimenter. Second, because of the shadowing requirement, all communication once the experiment started was nonverbal. The same nonverbal procedure was carried out with non-shadowing subjects, who listened to white noise. So that adults' spontaneous choice of strategy could be evaluated, no suggestions were made about using words or not using words before the experiment began. However following the experiment, adult subjects were asked whether they had used words.

Results

As already recorded in *Method / Subjects*, all 14 non-shadowing subjects reported that they had used words, which confirms a highly consistent preference in adults for a verbal strategy when one was available. By contrast, only one shadowing subject (of 13) reported using words, *i.e.* the shadowing procedure was successful in eliminating verbal strategies in the rest. These subjects were analysed as "non-verbal", whereas all non-shadowing subjects plus the shadowing subject who did use words were analysed as "verbal".

Figure 19 plots mean performance scores for "verbal" and "non-verbal" adults and children. Performance in "verbal" adults (top right) approached ceiling, although a small effect of condition was apparent. Performance in "non-verbal" adults (top left) was somewhat lower than this, but greatly exceeded performance in "non-verbal" 5-7 year olds (bottom left). Therefore even those adults deprived of language outperformed 5-7 year old children who were apparently not using language.

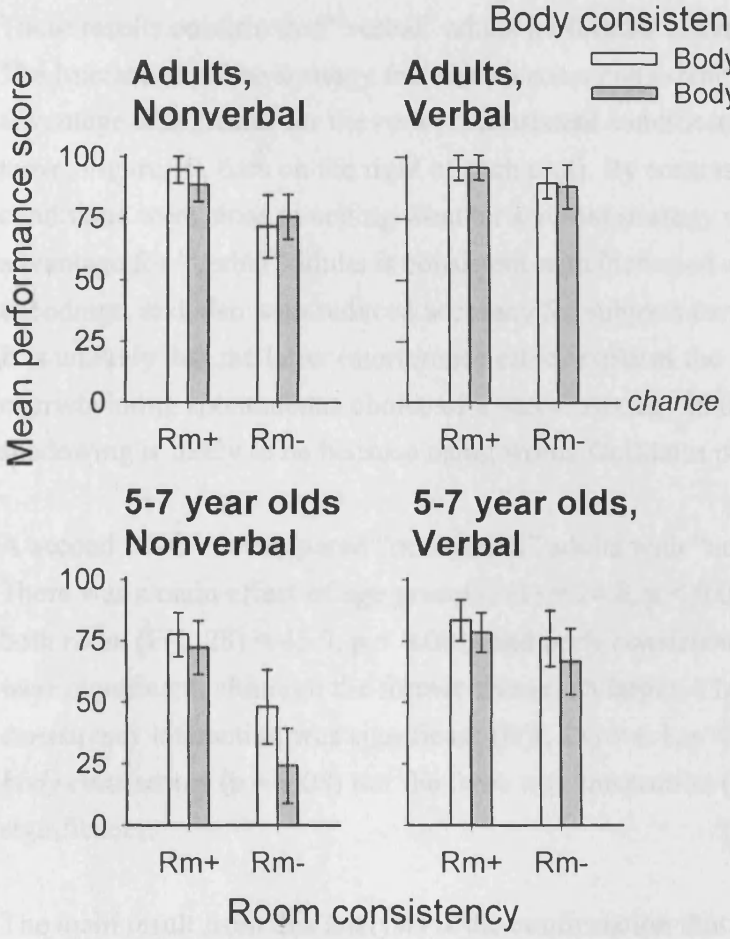


Figure 19. *Mean performance scores (95% confidence intervals) for "non-verbal" (left) and "verbal" (right) adults (top) and 5 - 7 year olds (bottom). White bars: body frame of reference consistent between presentation and test. Grey bars: body frame of reference inconsistent. Columns on the left: room frame of reference consistent between presentation and test. Columns on the right: room frame of reference inconsistent. The order of conditions, left to right, is therefore neither-move, child-move, both-move, array-move.*

The "verbal" group of children (bottom right) performed better than the "non-verbal", which is consistent with the predicted advantage for use of a verbal strategy, and also with their higher average age (6.4 compared with 5.7 years).

"Non-verbal" and "verbal" adults were first compared in an ANOVA. There was a main effect of *strategy* ($F(1) = 8.2$, $p < 0.01$). The overall effect of *room consistency* was significant ($F(1, 25) = 40.0$, $p < 0.001$), but the overall effect of *body consistency* was not ($F(1, 25) = 0.8$, $p > 0.7$). Of the interactions, only *strategy* x *room consistency* was significant ($F(1, 25) = 7.8$, $p < 0.01$).

These results confirm that "verbal" adults performed better overall than "non-verbal". The interaction of the strategy factor with *room consistency* shows that the "verbal" advantage was greater for the *room*-inconsistent conditions (*both-move* and *array move*; Figure 19, bars on the right of each plot). By contrast, the *room-consistent* conditions were close to ceiling whether a verbal strategy was available or not. The advantage for "verbal" adults is consistent with increased accuracy for verbal encodings, and also with reduced accuracy for subjects carrying out a concurrent task. It is unlikely that the latter interference effect explains the whole advantage, as the overwhelming spontaneous choice of a verbal strategy in those subjects who were not shadowing is likely to be because using words facilitates performance.

A second ANOVA compared "non-verbal" adults with "non-verbal" 5 - 7 year olds. There was a main effect of *age group* ($F(1) = 24.8$, $p < 0.001$). The overall effects of both *room* ($F(1, 28) = 45.9$, $p < 0.001$) and *body consistency* ($F(1, 28) = 4.4$, $p<0.05$) were significant, although the former was much larger. The *age group* x *room consistency* interaction was significant ($F(1, 28) = 6.1$, $p < 0.02$). Neither *age group* x *body consistency* ($p = 0.08$) nor the three way interaction ($p = 0.10$) reached significance.

The main result from this analysis is the confirmation that even among those probably not using language to represent the locations, a group of young adults who were not using verbal representations performed better than a group of 5 - 7 year olds who were not using verbal representations. This result strongly supports the hypothesis that nonverbal spatial representations continue to improve in accuracy beyond ages 5 - 7. The interaction with *room consistency* reflects an improvement in using the *array* frame of reference to solve the *room*-inconsistent conditions, and also the flattening-out of the adults' profile as their performance approached ceiling.

Discussion

The secondary verbal task would be predicted to reduce performance in shadowing adults somewhat, whether their performance depended on language or not. Indeed shadowing adults performed lower than those not shadowing. Nevertheless, adults who were shadowing outperformed those children aged 5-7 years who were apparently not following a verbal strategy. This interesting result supplements the finding, in Experiment 7, that very young children already have, and use, adult-like spatial representations. It suggests that these early-developing abilities are

nevertheless subject to a long and gradual development in accuracy. Furthermore, it shows that adults' improved performance is not only the result of a switch to using words to represent locations, but represents an improvement in the accuracy of nonverbal representations supporting spatial recall.

The continuing improvement in the condition consistent only with the *array* – and consequent reduction of the *room consistency* effect in the adult group compared with the children – indicates that object referenced, or "intrinsic" representations in particular continued to improve. These would support better recall on every condition. However it is difficult to evaluate whether *room* or *body* based representations also improved, since performance in the *room* and *body*-consistent conditions approached measurement ceiling.

A further question is whether the continuing accuracy improvements between childhood and adulthood might be supported by some factor external to spatial representations but involved in their encoding and retrieval, such as attention. It is possible that attentional and working memory improvements in late childhood contribute to performance on this task. However it would be difficult to test this experimentally in a way that would allow the contribution of these factors to be quantified.

CHAPTER 5

Spatial frames of reference in atypical development

5.1 Experiment 9

The detailed pattern of normal results from Experiment 7 (p. 89) provides a basis for assessing performance in clinical groups. The present experiment returned to subjects with Williams Syndrome (WS; see Experiment 6, p. 83). Comparison with the normal results should show whether spatial representations in WS are either globally delayed or specifically impaired. Current hypotheses about the Williams Syndrome visuospatial deficit suggest an impairment in dorsal-stream processing (Atkinson *et al.*, 1997; Atkinson *et al.*, 2003; Paul *et al.*, 2002), paralleled by functional anomalies in parietal cortex (Meyer-Lindenberg *et al.*, 2004) and hippocampus (Meyer-Lindenberg *et al.*, 2005). Both parietal and hippocampal impairments would predict reduced use of the *room* frame of reference, which is hypothesised to depend in part on parietal sensorimotor updating and in part of hippocampal coding of landmarks. By contrast, shape recognition and configural processing, dependent on the ventral stream, are reported to be less impaired in Williams Syndrome (Paul *et al.*, 2002, Vicari *et al.*, 2005). In the present design, consistency with the *body* frame of reference equates to the availability of a familiar view of the array. If relative sparing of ventral-stream representations in WS extends to viewpoint-dependent representations of scenes, *e.g.* in parahippocampal cortex (Epstein & Kanwisher, 1998), this would predict relatively more reliable use of the *body* than the *room* frame of reference.

In addition, individuals with Williams Syndrome perform poorly on "frontal" inhibition tasks (Atkinson *et al.*, 2003), particularly when the response that has to be inhibited is spatially directed (for example, the counter-pointing test, where the task is to touch the opposite side of the screen when a target appears). There is also evidence for organisational abnormalities of the frontal lobes (Reiss *et al.*, 2004a). It has been suggested that use of an object-centred (intrinsic) *array* frame of reference, and inhibition of the incorrect *body* and *room* frames, may have a frontal component (Experiment 7, *Discussion / Neural Correlates*; p. 110). A frontal anomaly could prevent Williams Syndrome individuals from mastering viewpoint-independent recall (*array-move* condition).

Method

Subjects

Participants were 9 children (5 male) with Williams Syndrome aged 8 - 15 years (mean age 11.4, s.d 2.1 years) and 25 adults (9 male) aged 16 - 44 years with Williams Syndrome (mean age 27.1, s.d. 8.2 years). Participants were tested at the Williams Syndrome Foundation convention, Preston, and at the Visual Development Unit, London. Results were compared with the 73 typically developing children aged 3 - 6 years who participated in Experiment 7 (see *Method*, p. 93).

A measure of verbal age was obtained for each subject on the British Vocabulary Picture Scale (BPVS), short form (Dunn, Dunn, Whetton, & Pintillie, 1982). Mean verbal ages were 7.4 (s.d. 2.0) years for the 8 - 15 year old group, and 10.0 (s.d. 3.1) years for the adult group. The BPVS is not able to measure verbal ages above 16, however only three subjects, all in the adult group, approached this ceiling. For some analyses, a median split based on this verbal measure of development further subdivided the adult group. The "low verbal" group comprised 12 adults (3 male) with mean chronological age 25.1 (s.d. 8.0) years and mean verbal age 7.5 (s.d. 1.4 years). The "high verbal" group comprised 13 adults (6 male) with mean chronological age 28.9 (s.d. 8.2) years and mean verbal age 12.5 (s.d. 2.4) years.

Apparatus, Design, and Procedure

The apparatus, design, and procedure were the same as for Experiment 7 (p. 93).

Results

The top half of **Figure 20**Figure 20 (a, b) replots normative data from Experiment 7. The lower half plots the Williams Syndrome data collected in the present experiment. Mean performance scores are shown in (c) and (d) for 8 - 15 year olds (left) and adults (right) with WS. (e) and (f) subdivide the adult WS group by verbal age. It is clear that performance in both 8 - 15 year old and 16 - 44 year old groups with WS was very low compared with the young controls. The adult group (c, right) looks well matched to typical four year olds (a). A subdivision by verbal age within this group (e) shows a very minor advantage for "high verbal" subjects.

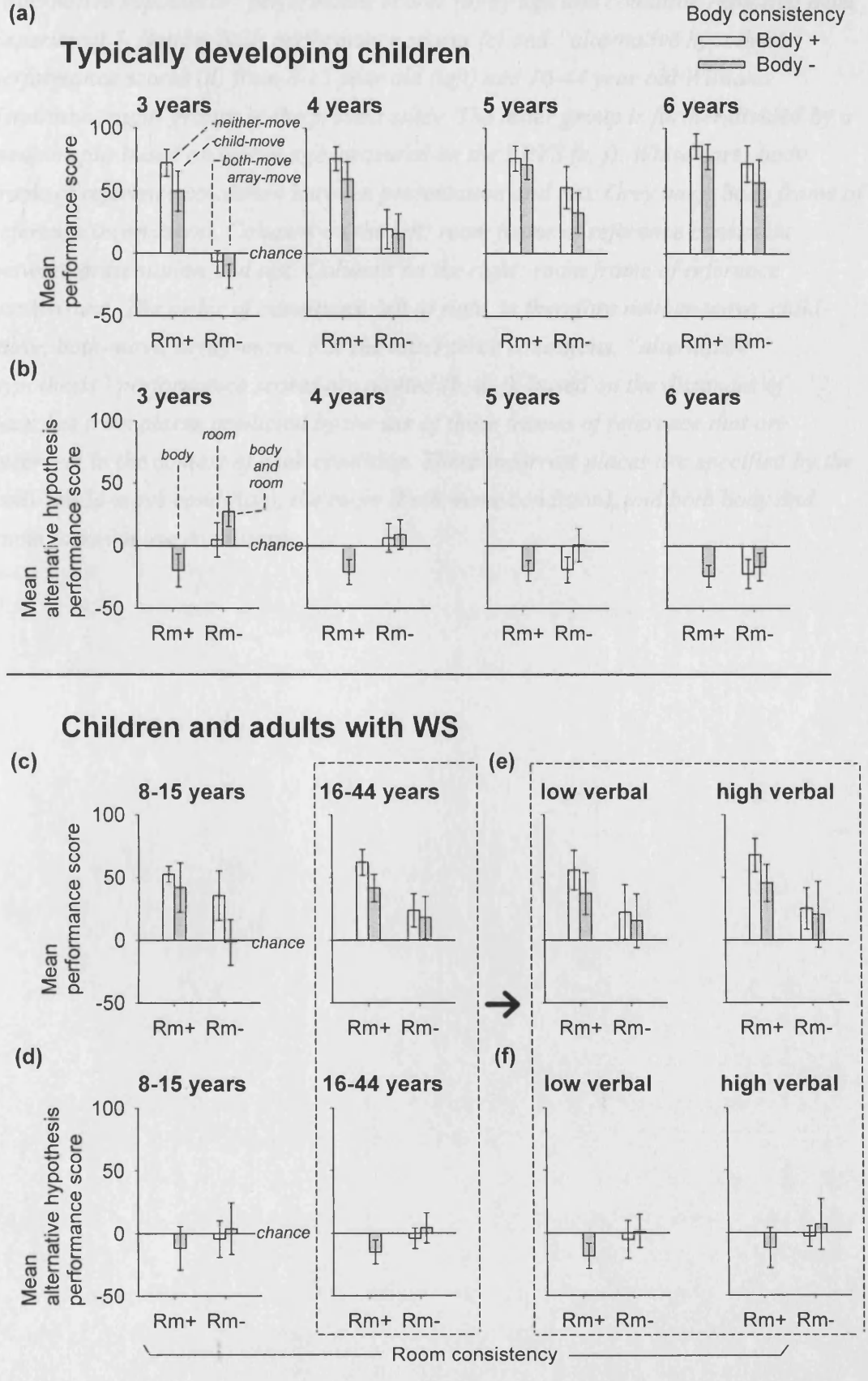

(a)
Typically developing children
Body consistency
Body +
Body -
3 years
4 years
5 years
6 years
neither-move
child-move
both-move
array-move
chance
Mean performance score
100
50
0
-50
Rm+ Rm-
(b)
body
room
body and room
Mean alternative hypothesis performance score
Children and adults with WS
(c)
8-15 years
16-44 years
(e)
low verbal
high verbal
(d)
(f)
Room consistency

Figure 20. *Top half: performance scores and 95% confidence intervals (**a**) and "alternative hypothesis" performance scores (**b**) by age and condition replotted from Experiment 7. Bottom half: performance scores (**c**) and "alternative hypothesis" performance scores (**d**) from 8-15 year old (left) and 16-44 year old Williams Syndrome (right) groups in the present study. The latter group is further divided by a median split based on verbal age measured on the BPVS (**e, f**). White bars: body frame of reference consistent between presentation and test. Grey bars: body frame of reference inconsistent. Columns on the left: room frame of reference consistent between presentation and test. Columns on the right: room frame of reference inconsistent. The order of conditions, left to right, is therefore neither-move, child-move, both-move, array-move. For the latter three conditions, "alternative hypothesis" performance scores are plotted (**b, d, f**), based on the distances of searches from places predicted by the use of those frames of reference that are incorrect in the context of each condition. These incorrect places are specified by the body (child-move condition), the room (both-move condition), and both body and room (array-move condition).*

The profile of the 8 - 15 year old WS group matches neither adults with WS nor any of the control groups. The unusual feature is a disjunction between the two *room*-inconsistent conditions (bars on the right), *both-move* and *array-move*. This can be described in two ways: *both-move* performance is unusually good for subjects who are so low on *array-move*, or *array-move* is unusually poor for subjects performing at this level for *both-move*. The 95% confidence intervals show that 8 - 15 year olds with WS were not above chance on the *array-move* condition. Adults with WS all considered together (c) were just above chance on this condition, although when they were divided by BPVS score (e) this effect was lost in both subgroups. The "alternative hypothesis" plots (b, d, f), show no evidence for consistent use of an inappropriate frame of reference for any condition in any of the groups with WS. Their poor performance was therefore not produced by a consistent error of this kind.

Two analyses were carried out. The first compared the two groups with WS to determine how chronological age and (in the adults) verbal age interacted with the spatial factors. The second analysis statistically confirmed the similarities and dissimilarities between the WS and the control data, visually evident in **Figure 20**Figure 20, to determine whether the WS results indicate either a global delay or a specific deficit.

Development in Williams Syndrome

Children and adults with Williams Syndrome were compared in an ANOVA with the factors *age*, *room consistency* and *body consistency*. There were main effects of *room* ($F(1, 32) = 25.1$, $p < 0.001$) and *body consistency* ($F(1, 32) = 12.6$, $p < 0.001$). The *room* x *body* interaction was not significant ($p > 0.5$). There was no main effect of *group* ($p > 0.6$). Neither *group* x *room* nor *group* x *body* were significant ($p > 0.9$; $p > 0.3$); however the three-way interaction *group* x *room* x *body* was significant ($F(1, 32) = 5.0$, $p < 0.05$).

The strong, non-interacting effects of *body* and *room* parallel those in typically developing children across the age range. Overall, these spatial factors had similar effects on retrieval for individuals with Williams Syndrome as they had for young children (Experiment 7): both were present, did not interact, and the *room* effect was stronger. The absence of an overall effect of *group* indicates that no developmental change corresponding to an overall improvement in performance occurred between 8 - 15 and 16 - 44 years. However the three-way interaction between *group* and the two spatial factors shows that *room* and *body* interacted differently in the two groups. This is evident in **Figure 20**Figure 20 c. In the 8-15 year old group, the effect of *body*

consistency (difference between white and grey bars) was small in the *room*-consistent conditions (bars on the left) but large in the *room*-inconsistent (bars on the right), whereas in the adult group the effect of *body consistency* was similar for both.

This developmental change - a changing interaction between *body* and *room* - does not correspond to any change recorded between 3 - 6 years in typical development (Experiment 7). There the changes were an overall effect of *group* (corresponding to a global improvement in performance) plus a *group* x *room* interaction corresponding to improving performance on both *room*-inconsistent conditions. The outcome of the developmental changes in the WS and the control data, however, is similar, in that it shows the emergence of an *array* based frame of reference (marginal in the case of the adults with WS), needed to solve the *array-move* condition.

To confirm the sizes of effects of *room* and *body* in the two WS groups, each group was placed individually in an ANOVA with the two spatial factors. In the adult group F-values for *room* and *body* effects were 22.2 and 5.7 respectively, whereas in the 8-15 year old group these values were 11.4 and 8.7. This shows that the large overall effect of *room* in the previous analysis was produced mainly by the larger adult group, and that as the interaction in that analysis indicates, the *room* advantage over *body* was much smaller in the 8 - 15 year old group.

Adults with WS were further subdivided by a median split based on verbal age, measured on the BPVS. This measure provided an assessment of development outside the spatial domain. "Low" and "high" adult groups were compared in an ANOVA. There were main effects of *room* ($F(1, 23) = 21.1$, $p < 0.001$) and *body* ($F(1, 23) = 5.4$, $p < 0.05$). The effect of *group* was not significant ($p > 0.4$), and there were no significant interactions. Therefore within the adult WS group, this verbal measure predicted neither overall performance, nor differential effects for the spatial manipulations.

Evidence for global delay or specific impairment

Figure 20 Figure 20 suggests that 16-44 year olds with WS closely matched typically developing 4 year olds, whereas 8 - 15 year olds showed an unusual pattern not seen in any control group. A set of ANOVAs assessed the "fit" between the WS data and control data of each of the ages 3, 4, 5, and 6 years. A nonsignificant main effect of *group* would show that the overall level of performance of a WS group and a control group was well matched. Nonsignificant interaction terms including *group* and the

spatial factors would show that the pattern of performance across conditions was also matched.

The outcome of these analyses, which are detailed in Appendix 2, was as follows. The 16 - 44 year old WS group closely matched typical four year old controls, both on overall level of performance and on profile across conditions. The 8 - 15 year old WS group, by contrast, matched typical 3 and 4 year olds on overall level, but did not match any group on profile. This confirms that their pattern of performance was unlike that in any control group aged 3-6 years. It could correspond to a pattern in normal development below three years.

Observations regarding verbal strategies

It might be asked whether individuals with WS, for whom language is an area of relative strength, benefit from encoding places verbally. Some of the places on this task, such as those near the centre, could only be encoded using fairly complex spatial terms (Experiment 7, **Figure 16**Figure 16; p. 95). It would not be surprising if individuals with WS, who find it difficult to discern such spatial relationships also find it difficult to put them into words. On the other hand, individuals who were asked to describe a toy on a final surprise verbal trial often answered correctly that it was "next to the cat", showing the ability to use words to describe simple, direct relationships between places and landmarks. Some subjects however did not seem to understand the relation between hiding places and landmarks at all, or its invariance as the array was rotated. This was the conversation between the experimenter and one participant, G.T., a 34-year old man with WS, after the experiment had finished, *i.e.* after 20 minutes' experience retrieving hidden objects from the array. G.T. had scored at chance on the *rotate* condition.

Exp: "I'm going to hide this one here. What's that next to?"
G.T.: "The post office"
Exp: "Will it still be near the post office when I turn the whole thing around?"
G.T.: "I don't know … we'd have to try it"
(Experimenter 2 walks back and forth with G.T. while experimenter one rotates the array – *i.e.* a *rotate* trial is carried out).
Exp: "What was it near?"
G.T.: "The post office."
(G.T. finds the hidden object!)

Prompted in this way, other individuals with WS who were unable to solve the *rotate* condition also found the object. Interestingly, this shows that supplying individuals with a verbal strategy that they had not thought to use by themselves could help their performance in some circumstances. This suggests that some kinds of verbal strategies might provide a useful intervention for spatial and navigational difficulties in individuals with WS.

Discussion

This study found that adults with Williams Syndrome used spatial frames of reference in a way that is normal for young children. Like typically developing four year olds, they showed parallel use of *body* and *room* frames of reference, which were combined additively when both were available. Also like four year olds, they showed very marginal evidence for viewpoint-independent retrieval on the *array-move* condition, *i.e.* correct use of the *array* frame of reference, dependent on object-centred or "intrinsic" representations.

These similarities between WS adults and typical four year olds suggest that development in WS was incomplete. Another explanation would be that spatial representations in WS were poor owing to a specific impairment. This is true in that use of the *array* frame of reference in particular was very low in WS adults; however as this frame of reference is the last to emerge in development, this "specific impairment" account is reducible to an "incomplete development" account. Whichever of these two ways the deficit is described, it is clear that on this task, adults with WS possessed and used both *body* and *room* based spatial representations well, but object-referenced representations only marginally.

Evaluating performance in younger individuals with WS is more difficult owing to the small number in the 8 – 15 year old group, and the lack of normative data below three years. The clear results were that the 8 - 15 year old group did not use the *array* frame of reference at all. They did use *body* and *room* – like controls and older WS subjects – but showed an interaction between these factors that was not seen in any other group. One consequence of this interaction was that relative to young controls also lacking an *array* frame of reference, 8 - 15 year olds with WS were unusually good at "ignoring" the array's position within the room and retrieving the toy relative to the body in the *both-move* condition (**Figure 20**Figure 20 c; third bar). One explanation for the correct selection of *body* over *room* in this condition would be if the *room* frame of reference were not used by the WS group. However the *room* frame of

reference must have been used to solve the *participant-move* condition (second bar), which was well above chance. The interaction shows specifically that *body* and *room* frames of reference were combined differentially depending on whether the array was *room*-consistent or not.

This suggests a different selection process for *body* and *room* dependent representations in the 8-15 year old WS group relative to controls. In the WS group, *room* was able to inhibit *body* (*participant-move* condition) but *body* was also able to inhibit *room* (*both-move*). In young controls *room* was able to inhibit *body*, but not the other way around. Older controls showed correct retrieval corresponding to inhibition of *body* and/or *room*, but these effects most likely involved use of the emerging *array* frame of reference. The 8 - 15 year old WS group were unusual in being able to select *body* over *room* dependent representations without additional help from *array* representations. Thus although the *room* frame of reference was present, it was more apt to be inhibited in the 8 - 15 year old WS group than in young controls. The atypical pattern of interplay between these two frames of reference in WS is consistent with a different balance for selection of dorsal and ventral information for action in this group relative to the controls.

It is possible that this pattern corresponds to a normal developmental stage before three years. The present task cannot be extended much below three. However if a task with the same factorial design were used for younger ages, the prediction from the classic studies on infant "egocentrism" (e.g. Bremner & Bryant, 1977) would be a stage at which, in terms of the plots from this study (**Figure 20**Figure 20), both white (body+) bars would be high, and both grey (body-) bars would be low. There would then be some pattern intermediate between this and the normal pattern seen at 3 years (Figure 20). This stage – at which the *room* frame of reference is emerging, but has not yet achieved its full dominance over the *body*, might correspond to where the 8-15 year olds with WS are.

It might be asked whether potential matches to young control groups are the best explanations of the visuospatial deficit in Wiliams Syndrome. Certainly cognitive development in WS, even within a single domain, needs more detailed explanation than a "delay", which suggests that developmental time had somehow simply gone slower. The assumption has been that a result does not qualify as a specific deficit until the "simpler" explanation of a global delay has been ruled out. The explanation for a global delay, however, is not necessarily simple. It suggests the involvement of widespread, rather than local, anomalies in the brain. Chromosome 7, the region of the WS deletion (Ewart *et al.*, 1993) includes genes coding elastin (*ELM*), LIM kinase 1 (*LIMK1*), and a cytoplasmic linker protein (*CYLN2*) (Hillier, Fulton, Fulton *et al.*,

2003). *LIMK1* and *CYLN2* may have a role in the WS cognitive deficit, as they are implicated in the development of neuronal structure and synaptic plasticity (Hoogenraad, Akhmanova, Galjart, & De Zeeuw, 2004). Although the neurodevelopmental effects of these deletions are not easy to predict, they are likely to be widespread. In the present adult data a global delay can behaviourally be described as a specific deficit in using object-referenced representations. The developmental explanation for this, however, is likely to be global.

One prediction in the Introduction was that WS individuals might show better use of the *body* frame of reference than the *room*, as body-referenced representations may tap ventral-stream scene and configural processing, reported to be an area of strength, whereas use of the *room* frame of reference may partly recruit the dorsal stream and parietal cortex, which are reported to be impaired or anomalous. The adult results did not support this: adults with WS used both *room* and *body* frames of reference, and indeed the *room* effect was stronger than the *body* effect, as it is in controls. The results from 8 - 15 year olds however were in partial support: in that group, the two effects were similar, so that the *room* frame of reference was much less dominant than it is in young controls.

There was also support for a second prediction, that viewpoint independent (*array* referenced) retrieval might be impaired, in line with reported frontal anomalies in WS. The failure of WS adults to go beyond the stage of typical four year olds would be explained if mastery of this frame of reference did indeed normally depend on frontal development post-age four, and if frontal development in WS was anomalous. This hypothesis is suggestive, but to address it satisfactorily more data are needed, both on neural correlates for this spatial memory task, and on brain development in Williams Syndrome.

Some individuals who were unable to use landmarks to solve the *rotate* condition showed that they could use them once prompted to use a verbal strategy. It is possible that some everyday spatial and navigational impairments in Williams Syndrome might possibly be overcome with an intervention, such as training in using words to remember landmarks.

5.2 Experiment 10

Studies with clinical populations serve two functions. First, they can improve the understanding of deficits in particular groups. Second, they can test hypotheses about structure-function relationships in normal development. For the second kind of analysis, structural differences in the clinical group must be well defined, ideally on a subject-by-subject basis.

The contribution of Experiment 9 was mainly to the understanding of Williams Syndrome. This study characterised the WS visuospatial deficit within the domain of spatial representation, and suggested that it was likely to depend on global neurodevelopmental factors. However as anomalies in brain organisation in WS are not well defined, and as no imaging data was available for individual participants, the study was not able to contribute a lot to the understanding of normal development.

The present study assessed a group of children aged 6 years whose brain development can be more accurately characterised. These were children born very premature, whose follow-up at the Hammersmith Hospital since birth has included a series of structural MR scans. The present study was carried out as part of a collaborative follow-up between the Visual Development Unit and the paediatric neuroimaging group at the Hammersmith Hospital; David Edwards, Mary Rutherford, Frances Cowan and Leigh Dyet. Additional developmental tests, described in the present study in a correlation analysis, were carried out by Shirley Anker and Dee Birtles (VDU), and Rachel Rathbone (Hammersmith). Qualitative MRI measures were categorised by Leigh Dyet and Mary Rutherford for this analysis. An existing set of quantitative MRI measures were also analysed; these were obtained by Olga Kapellou, Joanna Allsop and Morenike Ajayi-obe in a project run by David Edwards.

Very premature birth is associated with early neurodevelopmental impairment (Wood, Marlow, Costeloe *et al.*, 2000) and later cognitive and behavioural problems (Bhutta, Cleves, Casey *et al.*, 2002; Marlow, Wolke, Bracewell *et al.*, 2005). Destructive focal lesions are not common in this group, but the pressure of premature birth often results in mild but widespread developmental changes. White matter haemorrhages are common; at worst these can fill and significantly dilate the ventricles (intraventricular haemorrhage and ventricular dilatation). White matter lesions are also seen, the most serious being periventricular leukomalacia (PVL), a widespread atrophy of the post-periventricular white matter which is associated with visual, motor, and cognitive deficits (Volpe, 2001). At term-equivalent age and later, T2 weighted MR images of

premature brains often show areas of unusually high signal intensity in the post-periventricular white matter. This MR finding (Diffuse Excessive High Signal Intensity; DEHSI; Maalouf, Duggan, Rutherford *et al.*, 1999), which does not occur in normal term born infants, is of uncertain cause. It may be a sign of abnormal myelination. DEHSI may be predictive of poor cognitive outcome (Dyet, Kennea, Counsell et al., in press). In later childhood and adolescence, MR images of some children who were premature infants show a thin corpus callosum, which may also be predictive of cognitive deficits (Stewart, Rifkin, Amess *et al.*, 1999).

Premature birth is also associated with reduced cortical development - *i.e.* lower grey matter volume – at eight years (Reiss, Kesler, Vohr *et al.*, 2004b). Voxel-based morphometry (VBM) has identified reductions in cortical grey matter associated with specific deficits of cognition (calculation ability; Isaacs, Edmonds, Lucas, & Gadian, 2001) and perception (line orientation judgment; Isaacs, Edmonds, Chong *et al.*, 2003). A recent MRI analysis from the premature cohort of which the children in the present study were a subgroup showed that a reduced rate of early postnatal cortical surface area growth, relative to growth in volume, was associated with more premature birth, and predicted impairment on the Griffiths scale at two years (Ajayi-Obe, Saeed, Cowan *et al.*, 2000).

From the imaging data set available for the group in this study, two kinds of analyses are available. First, qualitative observations of discrete anomalies (*e.g.*, ventricular dilatation; thin corpus callosum) have been made from a series of scans ranging in from nenonatal age to six years. It could be determined whether these observations predict either overall or specific spatial memory impairments at six years. Second, for a subset of children, quantitative measures of cortical surface area and total cerebral volume at term-equivalent age were also available.

Neither these quantitative measures nor the qualitative observations provide local indexes of cortical anomaly. The quantitative measures relate to overall cortical growth, whereas the qualitative observations are most often of widespread white matter or ventricular changes. Voxel-based morphometry (VBM) was not suitable for this data set. The imaging data may therefore show global neurodevelopmental factors underlying spatial memory, but are not suited to finding localised neural correlates for specific functions. Global processes of growth and connectivity are of course crucial for normal development in all domains, including the visuospatial, and these measures are well worth investigating.

The children in this group also took part in a large set of other developmental tests as part of their follow-up at the Visual Development Unit, UCL, and the Hammersmith Hospital. Differential correlations between these tests and different conditions of the spatial memory task would provide evidence that cognitive and possibly neural substrates for these are separable.

In the preceding experiments, performance on the spatial memory task was analysed by group. Each individual's data, based only on four trials per condition, was quite noisy. This did not matter for the group analysis, however owing to the low sensitivity provided by only four trials it would have been difficult to show reliably whether a particular subject was above chance or not on a particular condition. To correlate individual MRI with individual behavioural results, the behavioural data from each subject must be reliable. The test was therefore changed to be suitable for individual assessment. First, the number of trials per condition was doubled to 8. As the number of trials increases, the error between experimental measures of performance and subjects' true ability should decrease. However the demand for additional trials could potentially increase variance (*e.g.* owing to subjects' inability to attend throughout the test). For this reason one condition (*both-move*) was dropped to keep testing to a feasible length. To make the score of each individual directly comparable with the score of every other, conditions and hiding locations were not randomised separately for every subject, but all subjects experienced the same standard set. The number of hidden objects on each trial was also increased to a maximum of 3, ascending in a staircase dependent on performance. It was hoped that this test would be sensitive to a wider range of abilities, and that it would also make it possible to establish age equivalences for the baseline (*neither-move*) condition which had previously shown a flat profile in typical development between 3 and 6 years (Experiment 7).

Method

Subjects

Premature group

In the premature group, 29 children (13 male) were tested on the spatial memory task at corrected age six years (mean corrected age, *i.e.* age from due date, 6.6, s.d. 0.23 years). One additional child did not complete the test. These children were born at the Hammersmith Hospital, London, at gestational ages 25.0 to 30.6 weeks (mean gestational age 28.2, s.d. 1.5 weeks). 27 children had a neonatal MR scan, and 24 had a scan at term-equivalent age (23 had both); 13 had a scan at 2 years, and 20 at 6 years.

Term and neonatal MRI showed mild changes (*e.g.*, mild DEHSI or minor ventricular dilatation) for 16 children, and more severe changes (*e.g.*, severe DEHSI, white matter lesions, significant ventricular dilatation) for 10. No child had indications of major destructive lesions. These findings, and those from MRI at 2 and 6 years, are given in detail in *Results*.

Quantitative measures of overall brain development, (1) total cerebral volume excluding cerebellum and ventricles and (2) cortical surface area, were available for 14 children at close to term-equivalent age (38 – 44 weeks).

At six years all children were able to walk and to communicate normally, and a majority attended normal classes and received no special help at school.

Control group

Normative data came from 80 typically developing children aged four to six years. This group represented a random sample of children at a London school and nursery, except that among the school-age children, any who received special one-to-one help were excluded. There were 36 four year olds (mean age 4.5, s.d. 0.27 years; 19 male), 20 five year olds (mean age 5.5, s.d. 0.24 years; 11 male), and 21 six year olds (mean age 6.5, s.d. 0.25 years; 12 male).

Apparatus

MR images were acquired with a 1.0 T MR imaging system (Oxford Magnet Technology / Marconi Medical) with full intensive care capacity. T2-weighted fast-spin echo images with a slice thickness of 4 mm acquired in the transverse plane were used for analysis. To measure volume and surface area, the boundary of the cortex in each transverse slice was traced using a contour following algorithm (Saeed, Hajnal, & Oatridge, 1997). Total cerebral volume was calculated from the total number of voxels (excluding those representing the ventricles and cerebellum). Cortical surface area was calculated from the number of surface voxels.

The apparatus for the spatial memory task was the array of landmarks and hiding places previously used for experiments 7 – 9 (see *Procedure*, below). The set of small toys whose positions had to be recalled was expanded so that some toys had two or three identical exemplars. These were used for trials with more than one object. Standard testing equipment was used for a series of other developmental tests; these tests are summarised in *Procedure*.

Design

Overall design of the study

Figure 21 summarises the overall design and the analyses undertaken. The use of different spatial frames of reference in the premature group was assessed by comparing these with the control group. Within the premature group, performance on the spatial memory conditions was also compared with performance on other developmental tests, to determine whether these correlated differentially. Finally, qualitative observations from MRI images, and quantitative measures from these, were also assessed as predictors of spatial performance in those subsets of the premature group for which these were available.

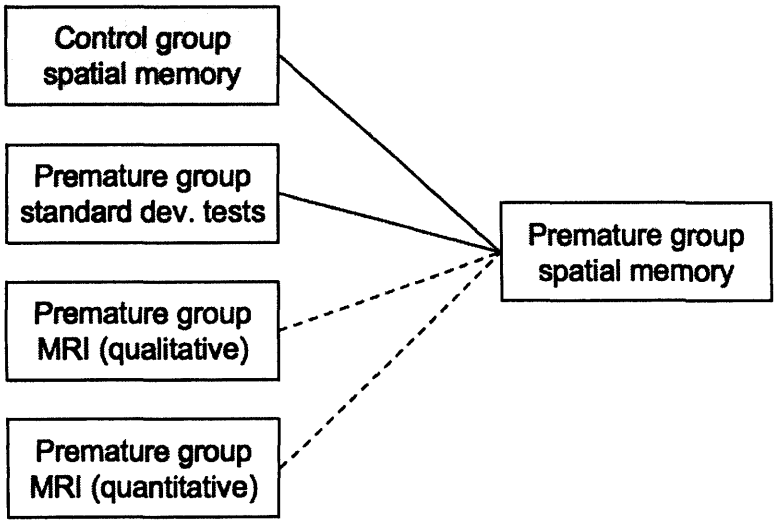


Figure 21. *Overall design for the study, with analyses undertaken to assess spatial memory in the premature group. Grey box: between-subjects comparison. White boxes: within-subjects comparison. Solid lines: measure available for all subjects. Dotted lines: measure available for a subset.*

Design for the spatial memory task

The spatial memory task included three conditions: *neither-move* (no viewpoint change), *child-move* (135° viewpoint change induced by self-motion), and *array-move* (135° viewpoint change induced by array rotation). **Figure 22**Figure 22 illustrates the conditions and the design. Unlike the preceding experiments this design did not test every combination of *body* and *room* based frames of reference. Instead, it compared a condition in which both of these plus the *array* frame of reference were available (*neither-move*) with one in which the *body* frame of reference was eliminated (*child-*

move), and one in which both *body* and *room* were eliminated (*array-move*). The *array* frame of reference, dependent on the use of landmarks at the edges of the array and/or its overall shape, was the only basis for recall on this last condition.

All participants completed a block of 16 trials, comprising 8 each of *neither-move* and *participant-move* in alternation. Those aged five years and above then completed an additional block of 8 *array-move* trials. In Experiment 7, ability to solve this condition was not the norm at ages three and four. Control group children in this age range, expected to perform at chance, were therefore not tested.

Performance was measured by the ability to find the exact hiding places of up to three toys. When more than one toy was hidden, the different toys were identical. Therefore when multiple locations had to be recalled, these did not have to be bound correctly with different objects. The task thus extended the previous experiments by placing an increased load on spatial memory, but did not introduce the novel (and distinct) demand of binding places with identities.

On each trial the number of searches allowed was one more than the number of hidden toys – that is, children who made an erroneous search were allowed one extra attempt. Three outcomes were possible: perfect retrieval needing no extra attempts, correct retrieval with the extra attempt needed, or failure to find all the toys even with the extra attempt. The number of toys hidden on each trial ascended and descended in a staircase as follows (see also **Figure 23**Figure 23). The first trial of every condition started with a single hidden toy. On a perfect retrieval, the number hidden on the next trial of that condition increased by one (to a maximum of three). On a correct retrieval needing an extra attempt the number of toys stayed the same for the next trial. On a failure to find all the toys, even with the extra attempt, the number hidden on the next trial decreased by one (to a minimum of one). As *neither-move* and *child-move* trials were presented in alternation, separate staircases for performance on these two conditions were maintained in parallel.

A score was awarded for each trial, correct retrieval of N toys scoring N points, with 0.5 deducted if the extra attempt was needed. Trials on which all toys were not found even after the extra attempt were scored 0. Each subject's final score for a condition was the sum of their scores on the 8 trials. As the number of trials was much too small to calculate a reliable threshold, this total score represented the most sensitive measure of performance on the test. Figure 23 illustrates the staircase rule, the probability of attaining each level of performance by chance, and the scoring scheme.

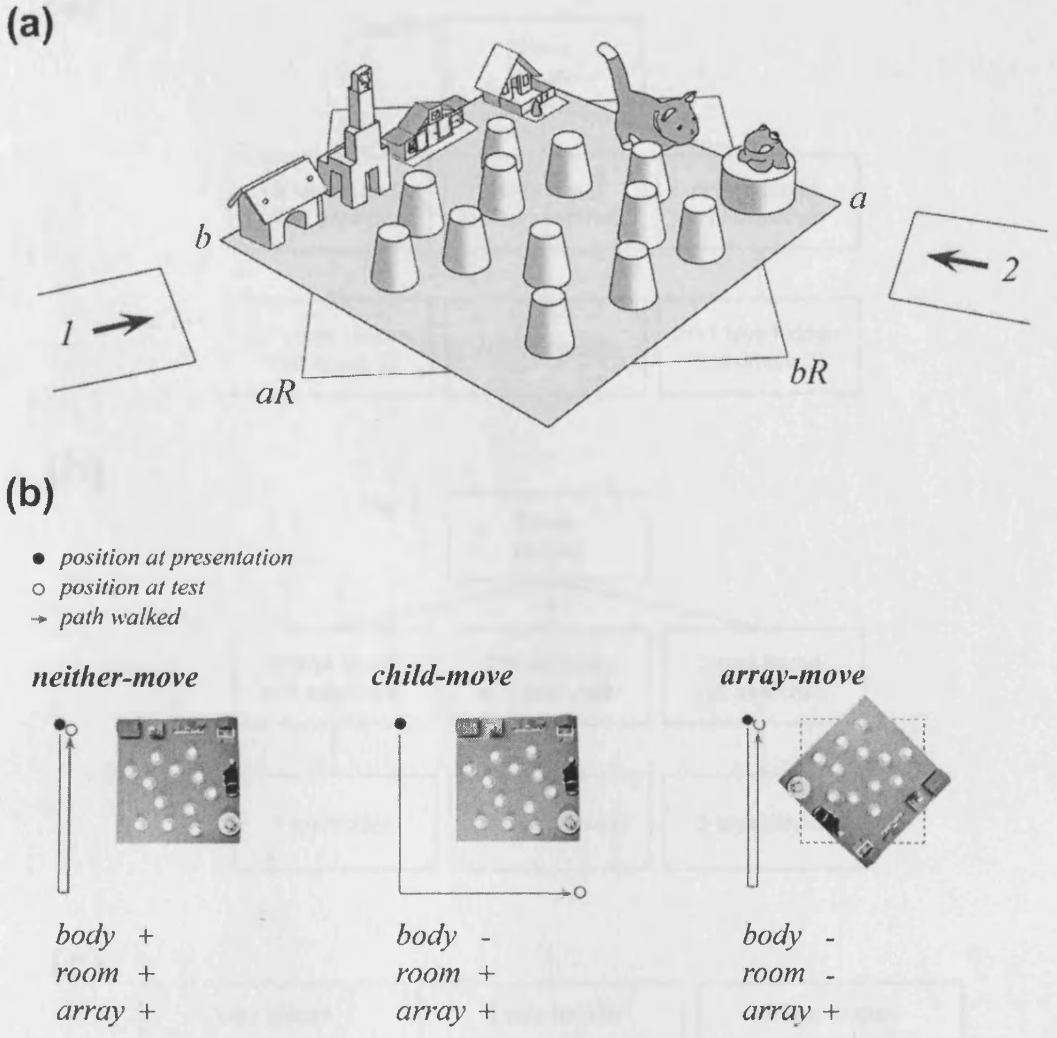
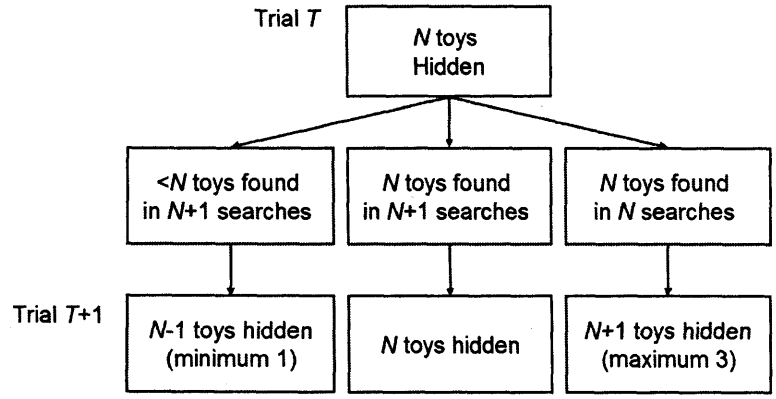
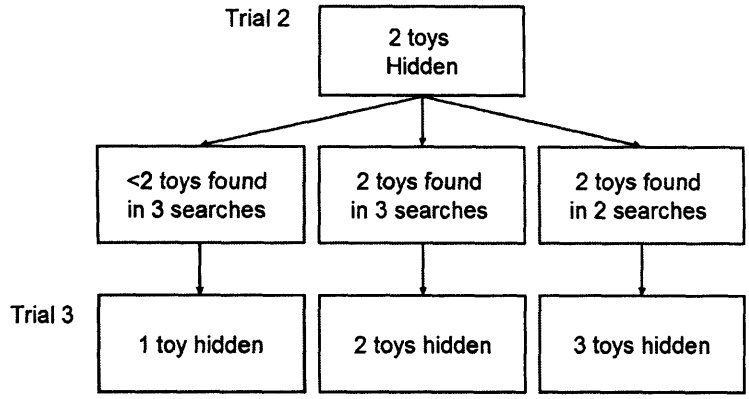


Figure 22: *the apparatus (**a**). After the toy was hidden, children either viewed the array from the same viewpoint (neither-move condition; e.g. walk from 1 halfway to 2, and back to 1), from a viewpoint shifted 135° by self motion (child-move condition; e.g. walk from 1 to 2), or from a viewpoint shifted 135° by array rotation (array-move condition; e.g. board rotates a to aR while participant walks from 1 halfway to 2, and back to 1). These three conditions (**b**) varied the hiding place's consistency with the body and the room. The frame of reference provided by the array was always consistent between presentation and test. This frame of reference provided the only basis for correct retrieval in the array-move condition.*

(a)



(b)



(c)

1 toy hidden		2 toys hidden		3 toys hidden	
Found in 2	Found in 1	Found in 3	Found in 2	Found in 4	Found in 3
p = 16.7%	p = 8.3%	p = 4.5%	p = 0.8%	p = 0.3%	p = 0.08%
score 0.5	score 1	score 1.5	score 2	score 2.5	score 3

Figure 23. *(**a**) the staircase rule for any starting number of toys N. The maximum number of searches allowed was always N+1. Performance determined the number of toys hidden on the next trial. (**b**) illustrates how the rule would be implemented on a 2-toy trial. (**c**) shows the scoring scheme by type of trial, outcome, probability of finding the toy(s) by chance, and score awarded. Trials on which all N toys were not found given N+1 attempts scored 0.*

Hiding locations in the staircase were in a pseudo-random sequence, which was the same for every subject. This sequence was generated with the following constraints. Each cup was used equally often on average, except the centre cup which was unused, as in Experiment 7, because it is not significantly displaced by rotation of the array. The same cup was never used on two successive trials. As one hidden object can serve as a landmark for another, on 2- and 3-toy trials the proximity of hidden toys was controlled: the number of immediately adjacent locations (1) within the same trial, and (2) between successive trials, were the same across the three conditions. These were set to the median number of within- and between-trial adjacencies occurring in 10,000 randomly generated sequences.

Procedure

Spatial memory task

The procedure for the spatial memory task was essentially the same as for the previous experiments (see Experiment 7, *Procedure*; p. 96). One experimenter hid toys and recorded responses while a second walked with the child. The experimenters ensured that they had the child's attention before beginning each trial. When more than one toy was hidden, children were told how many would be hidden and encouraged to attend carefully. Once all toys were hidden, the second experimenter walked the participant either all the way around the array and to the other viewing position, or halfway and back, holding a large sheet of card to one side of the child's face to block their view of the array. In the search phase, children were asked to use a ruler to tap the cup(s) where the toy(s) were hidden, and an experimenter lifted these. Each cup was lifted before the next search.

Participants who made their first error on a trial were told that they were allowed to keep looking. For those who made more than one error the trial ended regardless of the number of toys hidden, as the condition of finding N toys in no more than N+1 trials could now not be met. Those who had already made one error were warned that they had to find the remaining toy(s) without making any more errors. Throughout the study children were encouraged not to be impulsive but to think carefully before searching.

All children were tested on *neither-move* and *subject-move*. Those aged five years and above were additionally tested on a block of *array-move* trials. Before these began the experimenters carefully demonstrated how the array could be turned, and on all

subsequent *array-move* trials, children were warned before they searched that the array had "turned around".

Other developmental tests

Children in the premature group also took part in a large number of developmental tests, including tests of vision, attention, motor coordination and language. To test for differential cognitive demands (and potentially, dissociable neural bases) for the different spatial frames of reference tested in the spatial memory task, performance on each spatial memory condition was correlated with performance on each of the other tests. These tests are summarised with references in Appendix 3. These tests, which provide a lot of data, are not the main focus of this analysis. The analysis addresses them only insofar as they are able to indicate differences between the cognitive or neural substrates for the use of different frames of reference in the spatial task.

Results

Performance on the spatial memory task

Figure 24 Figure 24 plots scores by condition for control groups aged 4, 5, and 6 years, and for the premature group aged 6 years. Means and 95% confidence intervals are plotted at the top, and scores from individual participants are plotted below. Mean scores for every condition were well above chance in every group. Four year old children in the control group, who were not expected to be above chance on *array-move* (based on results from Experiment 7), were not tested on this condition.

In the control group, improvements with age can be seen for every condition. By 6 years there was no advantage for *child-move* over *array-move*. The testing sequence, in which *array-move* trials always came last (as they were not used for younger children), may have improved performance on this condition. ANOVAs were carried out to confirm that the control group showed improvement with age for each condition, and that all conditions were therefore sensitive indicators of development. Effects of *age group* were strong and highly significant for every condition: for *neither-move*, $F(2)=23.6$, $p<0.001$; for *child-move*, $F(2)=6.9$, $p<0.01$, and for *array-move* (which included only two age groups) $F(1)=7.6$, $p<0.01$.

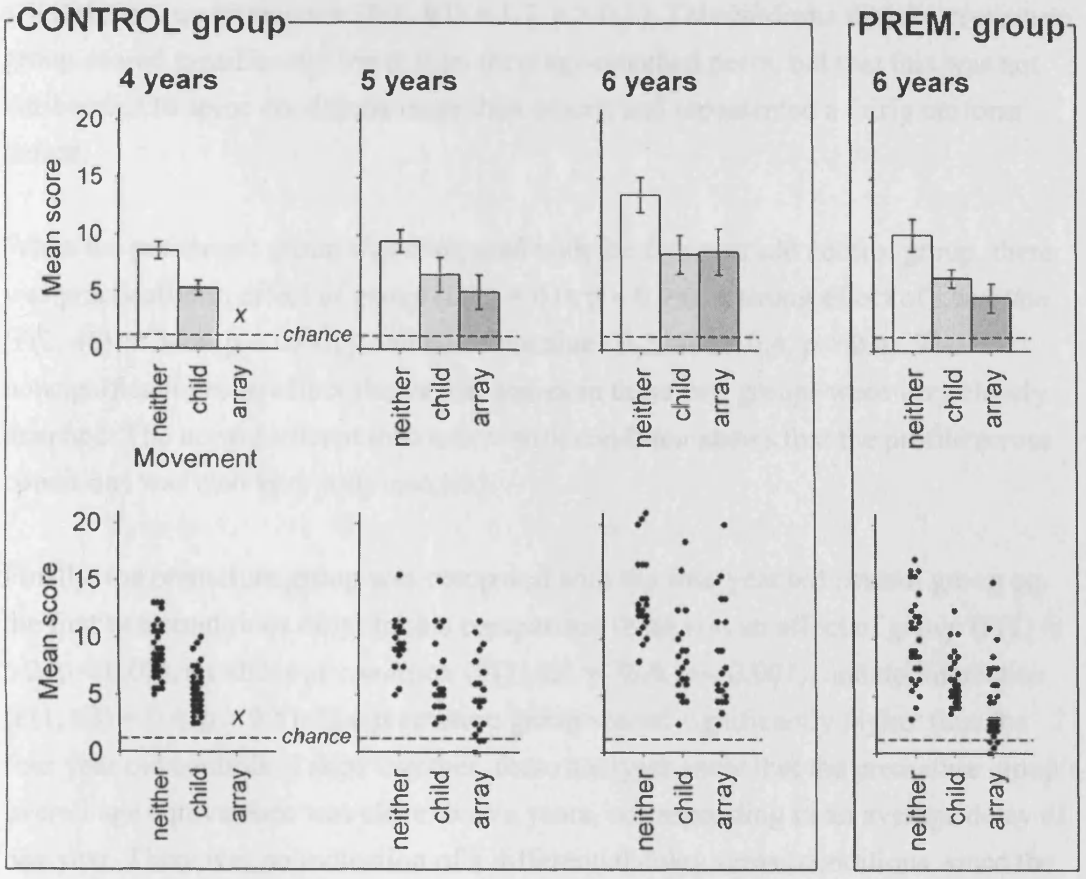


Figure 24. *Mean scores (95% error bars) by group and condition (top), and scores for individual children (bottom). Four year old controls were not tested on the array-move condition.*

As **Figure 24**Figure 24 shows, in the premature 6 year old group (mean adjusted age 6.6 years), mean performance was reduced compared with the 6 year old control group (mean age 6.5 years). The premature group closely matched the five year old control group (mean age 5.5 years) on every condition. This suggests an overall delay of around a year for the premature group, but not a differential pattern of delays across conditions. The pattern of impairment in the premature group seems not to be explicable by a minority of outliers reducing the mean for an otherwise normal group. The ranges and variances are quite similar to those in the "matching" 5 year old group (see error bars and scatter plots).

The premature group was compared with each control group in an ANOVA. Compared with the six year old group (who were matched on chronological age) there were main effects of *group* ($F(1) = 19.0$, $p < 0.001$) and *condition* ($F(2, 47) = 37.4$, p

< 0.001), but no interaction ($F(2, 47) = 1.7$, $p > 0.1$). This confirms that the premature group scored significantly lower than their age-matched peers, but that this was not attributable to some conditions more than others, and represented a fairly uniform deficit.

When the premature group was compared with the five year old control group, there was practically no effect of *group* ($F(1) = 0.0$, $p = 0.99$), a strong effect of *condition* ($F(2, 46) = 34.8$, $p < 0.001$), and no interaction ($F(2, 46) = 0.4$, $p > 0.6$). The nonsignificant *group* effect shows that scores in these two groups were very closely matched. The nonsignificant interaction with *condition* shows that the profile across conditions was also very well matched.

Finally, the premature group was compared with the four year old control group on the first two conditions only. In this comparison there was an effect of *group* ($F(1) = 6.2$, $p < 0.02$), an effect of *condition* ($F(1, 63) = 75.9$, $p < 0.001$), and no interaction ($F(1, 63) = 0.4$, $p > 0.5$). The premature group scored significantly higher than the four year old controls. Taken together, these analyses show that the premature group's overall age equivalence was close to five years, corresponding to an average delay of one year. There was no indication of a differential delay across conditions, since the profile across conditions closely matched the five year old profile.

Dissociations in individual children

Although there was no evidence that premature children considered as a group were impaired relative to controls on one condition more than on any other, it could still be the case that individual children showed dissociations between different conditions, consistent with specific impairments. This analysis therefore examined differences between conditions within subjects.

First, baseline measures were taken of dissociations between conditions in individual children in the control group. These were used to establish how many children in the premature group showed dissociations that were unusually strong. A dissociation between conditions that is unusual at control age 6 might potentially be a usual pattern for a younger child. For this reason, all children in the control group were included in the calculation of dissociations for comparison.

The first dissociation was between *neither-move* and *child-move* – *i.e.* between retrieval from the same viewpoint and retrieval after walking to a new viewpoint. The difference between these (see Figure 22, p. 135) was the availability of a *body* frame

of reference in the former condition but not the latter. The second dissociation was between *child-move* and *array-move* – that is, between retrieval from a novel viewpoint produced by walking, and retrieval from a novel viewpoint produced by rotation of the array (see Figure 22, p. 135). The difference between these was the availability of the *room* frame of reference. For this measure, only control-group children aged 5 and 6 (who did the *array-move* condition) were used.

For each child in the control group, scores were calculated expressing the difference between *neither-move* and *child-move* score (dissociation 1) and the difference between *child-move* and *array-move* score (dissociation 2). Means and standard deviations for these difference scores were calculated for the whole control group. These means were used to convert each control and premature child's difference score to a z-score, which expresses their distance from the control mean in standard deviations. Thresholds for unusual dissociations were set at 1.65 standard deviations above and below the mean, corresponding to the top and bottom 5% of difference scores respectively, and at 2.33 standard deviations above and below the mean, corresponding to the top and bottom 1%. Figure 25 shows the proportions of children in the control group and the premature group falling above and below these thresholds.

In the control group the upper and lower thresholds denoted very close to 5% and 1% of the group in both analyses (Figure 25 a, b; in b no control-group children met the 1% criterion, which is unsurprising as 1% in a sample of 41 predicts 0.41 children). The question was whether the extreme ends of the premature group's distributions, judged by these cutoffs, would be different.

In the comparison of *neither-move* and *child-move* (Figure 25 a), an elevated proportion of the premature group (3 / 29; 10.3%) were found in the "top 5%" (showing a strong *neither-move* advantage); one child (3.4%) was also in the "top 1%". Three of 29 (10.3%) were in the "bottom 5%" (showing a strong *child-move* advantage), and another one (3.4%) was in the "bottom 1%". However no child in the premature group showed a dissociation so strong that at least one typically developing child in 76 did not exceed it.

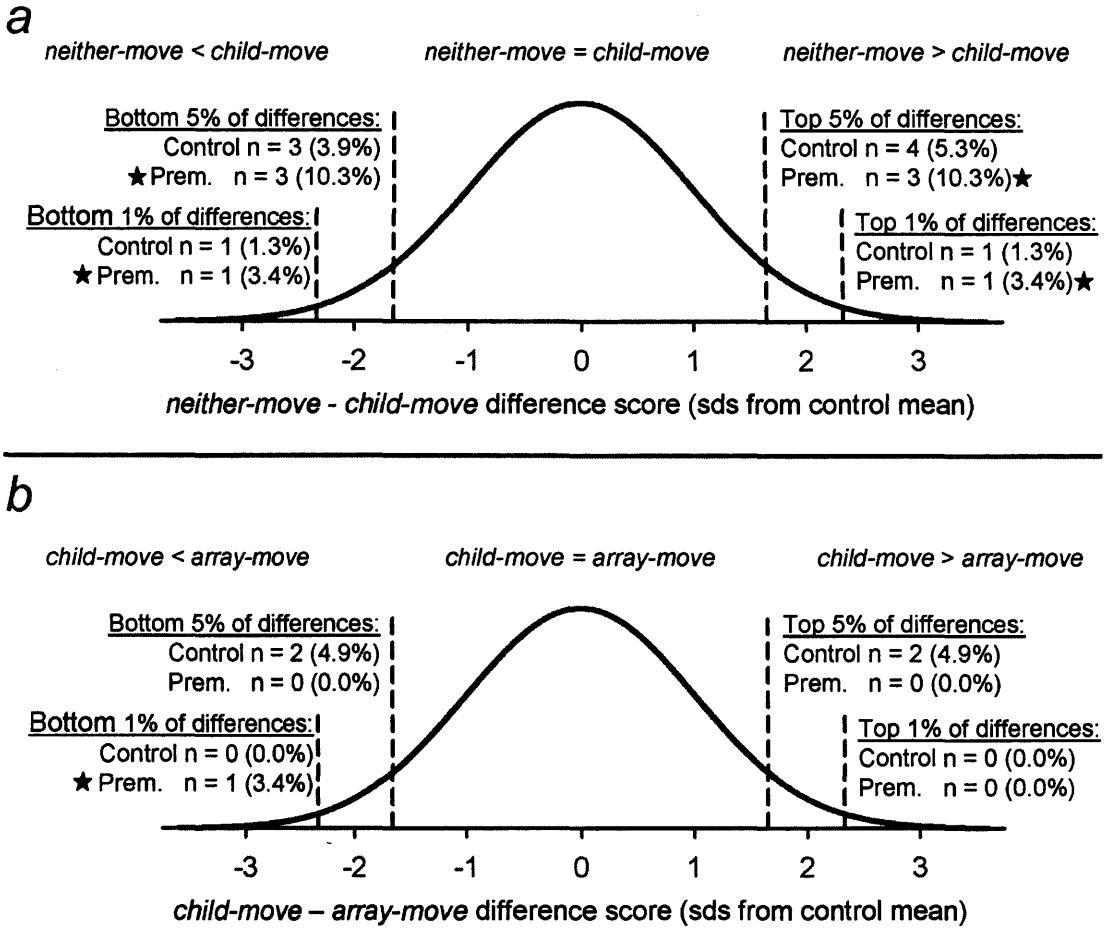


Figure 25. *Difference scores, expressed as standard deviations from the control group mean, for* ***(a)*** *neither-move - child move, where a high score corresponds to a strong neither-move advantage (and unusually poor use of the room frame of reference), and* ***(b)*** *child move - array-move, where a high score corresponds to a strong child-move advantage (and unusually poor use of the array frame of reference). Numbers and percentages of children in the control and premature groups falling beyond each threshold are shown. "*" marks where higher proportions of dissociations were found in the premature group than in the control group. The total number of children in the control group was smaller for* ***(b)****, as children aged 4 were not tested on array-move.*

Although rates of strong dissociations between *neither-move* and *child-move* were higher in the premature group, the proportion meeting the 5% criterion in the premature group, 6 of 29, did not differ significantly from the proportion in the control group, 7 of 76, on Fisher's exact test ($p = 0.11$). Among these (nonsignificantly) elevated dissociations, it is also surprising that those showing a strong advantage for *child-move* over *neither-move* were as numerous as those showing the opposite advantage. An elevated rate of *neither-move* > *child-move* dissociations would be consistent with specific impairments in nonegocentric spatial representations. The similarly elevated rate of *child-move* > *neither-move* dissociations however is puzzling. The marginally higher rate of strong dissociations in the premature group may therefore just denote higher trial-to-trial variability (owing for example to poor attention).

The second difference score, *child-move vs. array-move*, placed no premature children in either the "top 5%" or "top 1%". One in 29 (3.4%) was in the "bottom 5%", showing a large advantage for *array-move* over *child-move*. There is no evidence here for an elevated rate of dissociations in the premature group.

To summarise, there was no strong evidence for higher rates of strong dissociations consistent with specific impairments in the premature group. *Neither-move vs. child-move* were more frequent, but not significantly so, in the premature group. No dissociation was so strong that it was not matched in any of 76 controls.

Correlations with other tests

At the time of analysis, 26 of 29 children had completed all the developmental tests included in their 6-year follow-up at the Visual Development Unit and the Hammersmith Hospital. An exploratory analysis was undertaken with these results. Scores on each of the three spatial measures were correlated with scores on each standard developmental test. This analysis would show whether there were differential patterns of correlation for the three conditions, consistent with dissociations between their cognitive and possibly neural bases. Figure 26 a plots Pearson coefficients for correlations between scores on other developmental tests scores and scores on the different conditions in the spatial memory test. Where a higher score denoted worse performance (*e.g.* time taken on a timed test), the scores were inverted (multiplied by -1). A positive correlation on the graph therefore always indicates a positive correlation between ability on the two tests. Tests are grouped by their main demands.

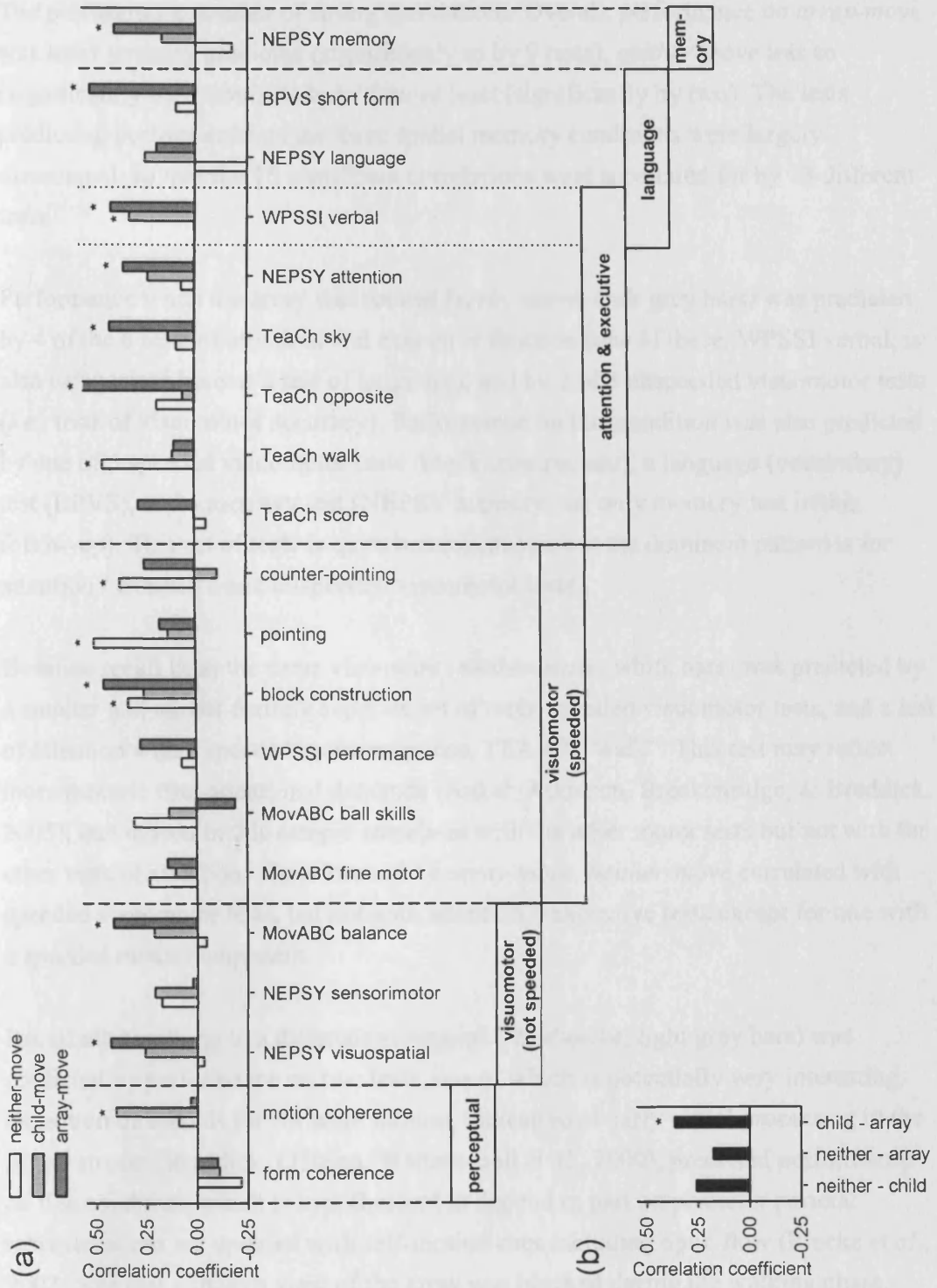


Figure 26. ***(a)*** *Pearson coefficients for correlations between scores on neither-move (white), child-move (light grey), and both-move (dark grey) conditions of the spatial memory test and scores on other tests (see Appendix 3 for details). "*": correlation significant at the 5% level on a one-tailed test. Tests are grouped by their main demands.* ***(b)*** *correlation coefficients between the three spatial memory conditions.*

The plot shows a number of strong correlations. Overall, performance on *array-move* was most strongly predicted (significantly so by 9 tests), *neither-move* less so (significantly by 4 tests), and *child-move* least (significantly by two). The tests predicting performance on the three spatial memory conditions were largely dissociated, so that the 15 significant correlations were accounted for by 13 different tests.

Performance when the array was rotated (*array-move*; dark grey bars) was predicted by 4 of the 6 tests of attention and executive function (one of these, WPSSI verbal, is also categorised here as a test of language), and by 2 of 3 unspeeded visuomotor tests (*i.e.,* tests of visuomotor accuracy). Performance on this condition was also predicted by one of 5 speeded visuomotor tests (block construction), a language (vocabulary) test (BPVS), and a memory test (NEPSY memory, the only memory test in this follow-up). This set of tests is quite heterogeneous, but the dominant pattern is for attention / executive and unspeeded visuomotor tests.

Baseline recall from the same viewpoint (*neither-move*; white bars) was predicted by a smaller and almost entirely separate set of tests: speeded visuomotor tests, and a test of attention with a speeded motor response, TEA-Ch "walk". This test may reflect more motoric than attentional demands (Anker, Atkinson, Breckenridge, & Braddick, 2005), and indeed in this sample correlates with the other motor tests but not with the other tests of attention. Therefore unlike *array-move*, *neither-move* correlated with speeded visuomotor tests, but not with attention / executive tests except for one with a speeded motor component.

Recall after walking to a different viewpoint (*child-move*; light grey bars) was predicted by performance on two tests, one of which is potentially very interesting. Detection thresholds for coherent motion, indicative of early visual processing in the dorsal stream (Braddick, O'Brien, Wattam-Bell *et al.*, 2000), predicted performance on this condition, which is hypothesised to depend in part on posterior parietal representations are updated with self-motion cues including optic flow (Riecke *et al.*, 2002; note that although view of the array was blocked during the walking phase, subjects did not walk without vision, but had optic flow from surroundings including walls and floor available). By contrast the coherent form test, which differs only in that the task it to detect coherent form, and is hypothesised to tap the ventral stream, showed no correlation at all (for more information on these tests, see Appendix 3, p. 194). The correlation between detection of coherent motion and *child-move* performance supports the hypothesis that performance after walking to a new point depends partly on dorsal-stream spatial representations updated with respect to optic

flow. **Figure 26**Figure 26 b plots Pearson coefficients for correlations between the three spatial memory conditions themselves. Only the correlation between *child-move* and *array-move* was significant at the 5% level on a one-tailed test. Neither-move did not significantly predict performance on either *child-move* or *array-move.*

To summarise, the correlations indicate that *array-move*, in which children had to use local landmarks within the array, had a strong attention / executive component: that is, it shared some demands with tests usually described as "frontal". This component could reflect the need to select the correct (array-centred) frame of reference, and to inhibit incorrect body- and room-centred frames. By contrast, *neither-move*, for which egocentric representations would suffice, correlated with a set of speeded visuomotor tests. These tests have in common the need to transform visual information for a spatially directed action, a posterior parietal function. *Child-move*, which could be solved partly by spatial updating with movement (path integration), correlated strongly with a test for perception of coherent motion, which supports the suggestion that path integration depends partly on optic flow processed by the dorsal stream.

These patterns of correlation with tests that did not involve memory or hidden objects suggest that the bases for use of different frames of reference in this clinical group drew on a variety of more general processes. The differential pattern of correlation across conditions suggests that these processes were also partly dissociable.

Predictors of performance from MRI (qualitative)

Figure 27 shows brain changes recorded on term-equivalent, 2-year and 6-year MRI in the premature group. Children's attendance at the different scan ages was variable (see *Method*).

On neonatal scans, the most common observation was a germinal layer haemorrhage (GLH; 12/26 scans). White matter lesions and intraventricular haemorrhages (IVH) were also seen, often co-occuring with GLH. Ventricular dilatation was only observed in three children, and IVH accompanied with ventricular dilatation only in one child. A caudate cyst was seen in one child with an otherwise normal scan; 8/26 had no abnormality observed.

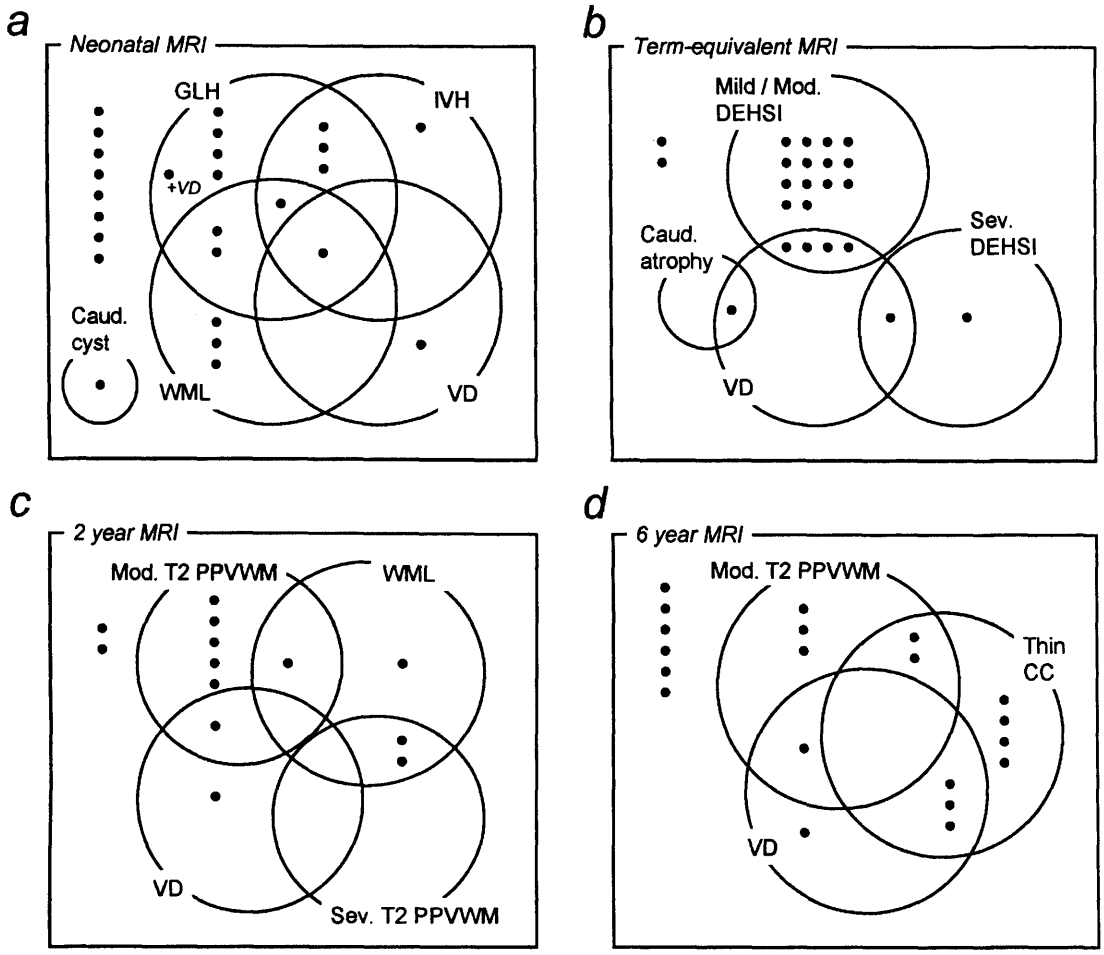


Figure 27. *Venn diagrams showing all children (dots) and observed anomalies (sets) on* ***(a)*** *neonatal,* ***(b)*** *term-equivalent age,* ***(c)*** *2-year and* ***(d)*** *6-year MRI. Children outside all sets are those who had a normal scan (no abnormality observed). GLH: germinal layer haemorrhage; IVH: intraventricular haemorrhage; WML: white matter lesion; VD: ventricular dilatation; Caud.: caudate; Mild / Mod. / Sev. DEHSI: mild / moderate / severe diffuse excessive high signal intensity on T2 weighted image; Mod. / Sev. T2 PPVWM: moderately / severely increased T2 signal in the post-periventricular white matter; Thin CC: thin corpus callosum. On the term scan the conjunction GLH and VD (only) could not be shown. One child with this combination is shown in GLH (only) marked "+VD".*

On term scans, a majority (19/23) showed mild or moderate DEHSI (diffuse excessive high signal intensity) in white matter on T2 weighted images; 2/23 showed severe DEHSI, while only two showed no DEHSI at all. DEHSI is a common finding on term-age scans of very premature children (Maalouf *et al.*, 1999), although its clinical significance is uncertain. 6/23 showed ventricular dilatation, in five cases this overlapped with DEHSI, in one case with caudate atrophy (seen only in one child); this was not the same child with an apparent caudate cyst on a neonatal scan. At this age only 2/23 children had no abnormality observed.

The number of children scanned at 2 years was only 13. Among these, a majority showed an increased signal on T2-weighted images in the post-periventricular white matter (a finding similar to DEHSI on neonatal scans); mild or moderate for 7/13 and severe for 2/13. Fewer children showed ventricular dilatation or white matter lesions, and these observations largely co-occurred with T2. Two of 13 children had a normal scan (no abnormality observed).

Twenty children were scanned at 6 years – the same period in which the spatial memory task was carried out. A common observation at this age was a thin corpus callosum (9/20). An increased signal in the post-periventricular white matter was seen on T2-weighted images in 6/14 and ventricular dilatation in 5/14; these observations largely co-occurred with each other and with thin corpus callosum. 6/20 children had no abnormality observed.

Predictors of spatial memory

To determine whether any of these MRI observations were predictive of later spatial memory, analyses was carried out to find sub-groups of children, categorised by MRI observations, who differed on 6-year spatial memory scores.

The overlap between categories is complex, and single factors can rarely be isolated. For example, ventricular dilatation – which was observed at all ages scanned – was almost always accompanied by at least one other observation (see **Figure 27**Figure 27). The most powerful way to analyse relationships between these overlapping observations and children's spatial memory scores at six years was provided by a clustering procedure, an exploratory technique that finds natural groupings in data sets with many dimensions. The procedure "Two-step cluster analysis" in SPSS 12.0 (SPSS Inc., Chicago, IL) was used. The algorithm in this procedure divides cases into clusters based on categorical and/or continuous variables where doing so reduces the likelihood distance measure for the whole data set. The number of clusters that provide the optimal solution is determined automatically.

Categorical variables (observations) and continuous variables (spatial memory scores at six years on *neither-move*, *child-move* and *array-move*) were entered into the procedure – initially separately for each scan age, then for various combinations of ages. Categories with only one member - caudate cyst (neonatal) and caudate atrophy (term) - were not entered into the model. The number of children in even the largest of these analyses (26 at neonatal age) was very small for a technique of this kind. Therefore at best it was hoped that two clusters might be found, one showing some reduction in spatial memory score. With much larger groups (and perhaps more detailed or localised observations) correlates of impairment differential across frames of reference in spatial memory might be found.

Figure 28 Figure 28 shows the results of the four initial cluster analyses. At each age, two clusters of cases were found, one cluster usually showing global (though small) reductions in mean spatial memory scores at six years. This was a trend that reached statistical significance in an ANOVA (within-subjects factor *condition*; between-subjects factor *cluster*) only in the term-equivalent age analysis (Figure 28 b). In the neonatal analysis an interaction term corresponding to an impairment specific to *neither-move* and *array-move* but not *child-move* for "cluster 2" children, was close to significance ($p=0.06$). In the 2 year and 6 year analyses p-values for main effects were 0.29 and 0.13 respectively.

Borderline significant results and nonsignificant trends have to be interpreted carefully in an exploratory analysis. If the difference between groups is difficult to interpret and not compelling on a test of statistical significance, the clustering might merely have provide a best fit for a data set with no inherent relation between MRI observations and spatial memory scores.

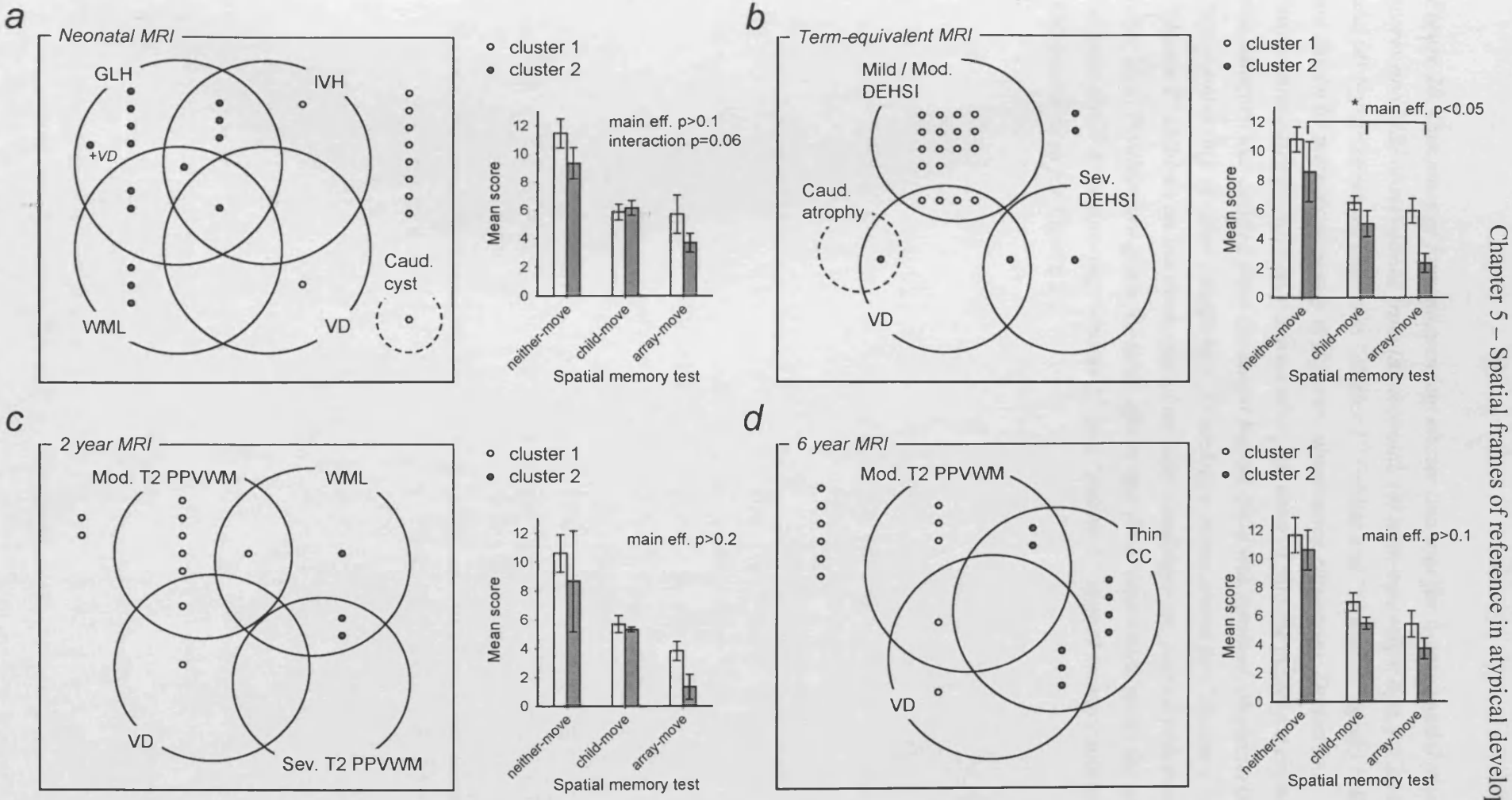

a
Neonatal MRI
GLH
IVH
+VD
Caud. cyst
WML
VD
cluster 1
cluster 2
main eff. p>0.1
interaction p=0.06
Mean score
neither-move
child-move
array-move
Spatial memory test
b
Term-equivalent MRI
Mild / Mod. DEHSI
Caud. atrophy
Sev. DEHSI
VD
cluster 1
cluster 2
* main eff. p<0.05
Mean score
neither-move
child-move
array-move
Spatial memory test
c
2 year MRI
Mod. T2 PPVWM
WML
VD
Sev. T2 PPVWM
cluster 1
cluster 2
main eff. p>0.2
Mean score
neither-move
child-move
array-move
Spatial memory test
d
6 year MRI
Mod. T2 PPVWM
Thin CC
VD
cluster 1
cluster 2
main eff. p>0.1
Mean score
neither-move
child-move
array-move
Spatial memory test

Figure 28. *Outcomes of four independent cluster analyses for 6-year spatial memory scores and MRI observations from* ***(a)*** *neonatal,* ***(b)*** *term-equivalent age,* ***(c)*** *2-year and* ***(d)*** *6-year scans. At each age "cluster 1" (white) and "cluster 2" (grey) children are shown by their membership of different observation categories. Dotted line: observation category with only one member, not entered into the model for clustering (the category was omitted from the model but the child was retained, characterised by their membership of other categories). At each age, mean scores for "cluster 1" and "cluster 2" children on the three spatial memory conditions are plotted with standard error bars. P-values are given for main effects and (in* ***a****) interaction terms for within-subjects ANOVAs comparing "cluster 1" and "cluster 2" spatial memory scores. Abbreviations as for Figure 27.*

Neonatal scans

The analysis of neonatal MRI (Figure 28 a) identified a cluster of lower-scoring subjects whose defining feature was GLH and/or white matter lesions. Children with no abnormality on scan, and those with IVH or ventricular dilatation but no GLH or white matter lesion, were in the higher-scoring cluster. The borderline ($p=0.06$) interaction term shows that children in the lower-scoring cluster were lower specifically on *neither-move* and *array-move*, but not on *child-move*. Early white matter damage might have lasting effects connectivity between different regions of cortex. The indication of a differential pattern across conditions is consistent with the suggestion that the neural basis for *child-move* is the most localised, *i.e.* depends mainly on the dorsal stream and posterior parietal lobe, whereas *array-move* recruits frontal processes and *neither-move* involves temporal representations.

Term-equivalent scans

In term-equivalent scans (Figure 28 b), the cluster analysis found two groups whose six-year spatial memory scores differed significantly at the 5% level. A higher-scoring group of 18 is distinguished by mild or moderate DEHSI (overlapping with ventricular dilatation in four cases), whereas a lower scoring group consists of everyone else: five others, including two with severe DEHSI and two with no observation of abnormality at all. Confusingly, this model states that mild or moderate DEHSI is associated with a better spatial memory outcome, whereas either no DEHSI or severe DEHSI is associated with a poorer outcome. However the cluster with mild/moderate DEHSI and "better" outcome still scored far below typically developing six year olds (see Figure 24, p. 139). Mild/moderate DEHSI should therefore be taken to signify a slightly lesser impairment, rather than no impairment.

The cluster without mild/moderate DEHSI in this sample is small and heterogeneous, so cannot be characterised well. The two children with no abnormality observed did score very low on spatial memory (as did one of the two with severe DEHSI). However this group of two "no abnormality" children is far too small to provide evidence that absence of DEHSI at term has a poor prognosis for spatial memory. The clearest conclusion that can be drawn is that at term, mild/moderate DEHSI is associated with a somewhat milder spatial memory deficit. However there is no single positive predictor of stronger deficits. Severe DEHSI could account for two of five, and caudate atrophy (a category with one member, not entered into the analysis) for one more. In the other two, such neural correlates of later spatial memory deficits as there were at term age were not observed qualitatively in these scans.

2-year scans

Analysis of 2-year MRI was hampered by the much smaller number of scans available: a cluster analysis of 13 data points distinguished by four categorical and three continuous variables hardly seems feasible. Nevertheless the procedure identified two clusters of cases (Figure 28 c). The higher-scoring group included all those with a moderately increased T2 signal in the post-periventricular white matter (a majority of subjects; 7/13; one of these also had a white matter lesion) as well as two with no abnormality and one with ventricular dilatation only. The lower-scoring group, numbering only three, included two with severely increased T2 and white matter lesions and one with a white matter lesion only. The difference between spatial memory scores was not significant ($p > 0.2$). It is worth noting that the trend for a moderately increased T2 signal – related to DEHSI at term age – to be associated with better scores at six years, and severely increased T2 with worse scores, is at least consistent with the term-age cluster analysis.

6-year scans

Results of the cluster analysis for six-year scans are perhaps the most credible and easy to interpret (**Figure 28**Figure 28 d). A lower-scoring cluster of 9 are distinguished by a thin corpus callosum. These observations partly overlap with moderately increased T2 and ventricular dilatation, however the 5 children with these observations and a normal corpus callosum fall into the higher-scoring cluster, along with 6 children with no abnormality on scan. The difference between spatial memory scores is consistent across conditions, but does not reach statistical significance ($p > 0.1$).

Taken together, these analyses show suggestive patterns in the data, but are hampered by the subject numbers, which are very small for methods of this kind. This may result in anomalies such as the grouping together of severe DEHSI and no DEHSI (but not mild/moderate DEHSI) as predictors of poor outcome at term-age.

Series of scans

It was asked whether entering a series of scans into a single analysis (*e.g.*, neonatal plus term) would, resulting in more within-subjects observations (though fewer subjects), provide more reliable clusters. Groups of scans were therefore entered into the analysis. Neither a neonatal + term analysis (comprising 22 children with 7 categorical MRI observations) nor a neonatal + term + six year analysis (16 children with 10 categorical observations) produced any clusters at all. This was almost certainly a function of the high ratio of variables to subjects. One further combination was attempted. To determine whether the association of mild or moderate DEHSI

(T2) with better spatial memory scores and severe DEHSI (T2) with worse scores could be confirmed within the same subjects at term and at 2 years, these two scans were entered. This analysis, comprising 11 children with 7 categorical observations, again produced no clusters. These analyses remain inconclusive owing to the small sizes of groups at present

To summarise, the qualitative data provided some indication that early brain changes could predict subsequent spatial memory scores. Although suggestive, the trends were far from being statistically reliable, especially for an exploratory technique. Three preliminary results are worth noting though. At neonatal age, germinal layer haemorrhages and white matter lesions may have a poor prognosis for spatial memory. At term age and at 2 years, mild or moderate DEHSI (which is a common finding) may not have an especially poor prognosis, however severe DEHSI may be a bad sign. At 6 years, a thin corpus callosum may be associated with spatial memory impairments. These initial hypotheses will be clarified with a larger group. When the collaborative study with the Hammersmith group is finished, there will be approximately three times as many subjects to analyse.

Predictors of performance from MRI (quantitative)

Finally, an analysis were carried out to determine whether either of two quantitative measures of brain development at term-equivalent age predicted spatial memory scores at six years. These measures were volume for the whole brain excluding the cerebellum and ventricles, and cortical surface area. Surface area is an important index of development, as the developing cortex undergoes convolution that entails a large increase in its surface. Most of this process of convolution takes place in early intrauterine and postnatal development. Volume and surface measures were available for 14 children (for selection criteria and ages at scan, see *Method / Subjects / Premature group*; p. 131).

To check that the 14 children in this analysis were representative of the total sample of 29, an ANOVA with within-subjects factor *condition* compared spatial memory scores of those included in the analysis with those excluded. There was no main effect of *inclusion* ($p > 0.2$) and no *inclusion* x *condition* interaction ($p > 0.4$). Therefore neither the overall level of performance, nor the pattern of performance across conditions, differed significantly between children included in this analysis and those excluded because no term-equivalent quantitative MR measures were available.

Cerebral volume and cortical surface area at close to term-equivalent age (38-44 weeks) were first adjusted for variations in age at scan. The same measure might be above average (for a premature child) if it came from a 38 week scan, but below average for 44 weeks. Measures were therefore converted to scores expressing how far above or below they were the average for a premature child scanned at that age. These averages came from a regression analysis which used all measures in the full Hammersmith data set (all scans at ages 38-44 weeks; n=51) to fit exponential curves relating each of cerebral volume and surface area to age at scan. These curves were used to convert each child's volume and surface area to a residual; that is, a difference score expressing how far it fell above or below the (premature) average for their age.

Figure 29 Figure 29 a plots term-equivalent cerebral volume and cortical surface area by age of scan. Regression curves derived from the full Hammersmith dataset are shown. Figure 29 b shows these measures converted to residuals based on the regression curves. Overall, surface and volume residuals were highly correlated with each other; $r^2 = 0.70$, $p<0.001$. Figure 29 c plots the correlation. Although the correlation holds for the whole data set, it is interesting to note that it does not describe the cluster of infants with the lowest surfaces or volumes well. There is a suggestion of a stronger dissociation between these measures in that subgroup.

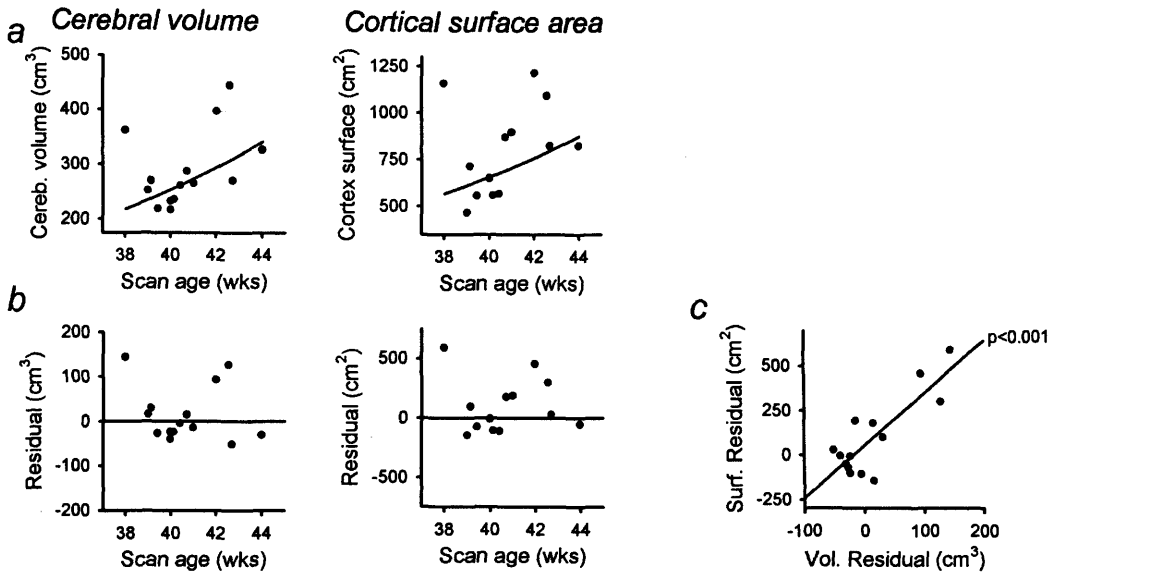
In Figure 29 d volume and surface residuals are plotted – now on the x-axis - against 6-year spatial memory scores. Two other potential predictors of performance, body weight at scan and gestational age at birth, are shown. Body weight was converted to a z-score, corresponding to the difference in standard deviations between each child's weight and the average weight for the child's (corrected) age. In this way the weight measure, like the two brain measures, was adjusted for each child's age at the time of the scan. As is usual for premature infants, the majority were well below average weight at term-equivalent age, although there was considerable variation in weight within the group.

There was a trend for both (residual) cerebral volume and (residual) cortical surface area[2] to predict 6-year performance on all three conditions of the spatial memory task; however no regression was significant at the 5% level. The most strongly predictive measures were neonatal volume *vs.* 6 year *array-move* score ($r^2 = 0.22$, $p = 0.089$), neonatal surface area *vs.* 6 year *array-move* ($r^2 = 0.22$, $p = 0.088$), and neonatal surface area *vs.* 6 year *child-move* ($r^2 = 0.22$, $p=0.090$). Body weight at scan and gestational age were much poorer predictors. One correlation, gestational age with

[2] All subsequent references to 'volume' and 'surface area' are to the transformed (residual) measure.

child-*move*, was in the expected direction, but was not as strong ($r^2 = 0.20$, $p > 0.1$) as the correlation of surface area with *child-move*.

To check for main effects of surface and volume on all spatial memory conditions considered together, and / or differential effects across different conditions, two ANOVAs were carried out, each with within-subjects factor *condition*, and either *cerebral volume* or *cortical surface area* as a covariate. These were not entered into the same analysis owing to their high degree of colinearity (see Figure 29 c). Total *body weight at scan* and *gestational age* were entered into these ANOVAs as two further covariates. These measures were included to separate any variance in spatial memory scores accounted for by consequences of premature birth unrelated to brain development.


a
Cerebral volume
Cereb. volume (cm3)
500
400
300
200
38 40 42 44
Scan age (wks)
Cortical surface area
Cortex surface (cm2)
1250
1000
750
500
38 40 42 44
Scan age (wks)
b
Residual (cm3)
200
100
0
-100
-200
38 40 42 44
Scan age (wks)
Residual (cm2)
500
0
-500
38 40 42 44
Scan age (wks)
c
Surf. Residual (cm2)
p<0.001
500
250
0
-250
-100 0 100 200
Vol. Residual (cm3)

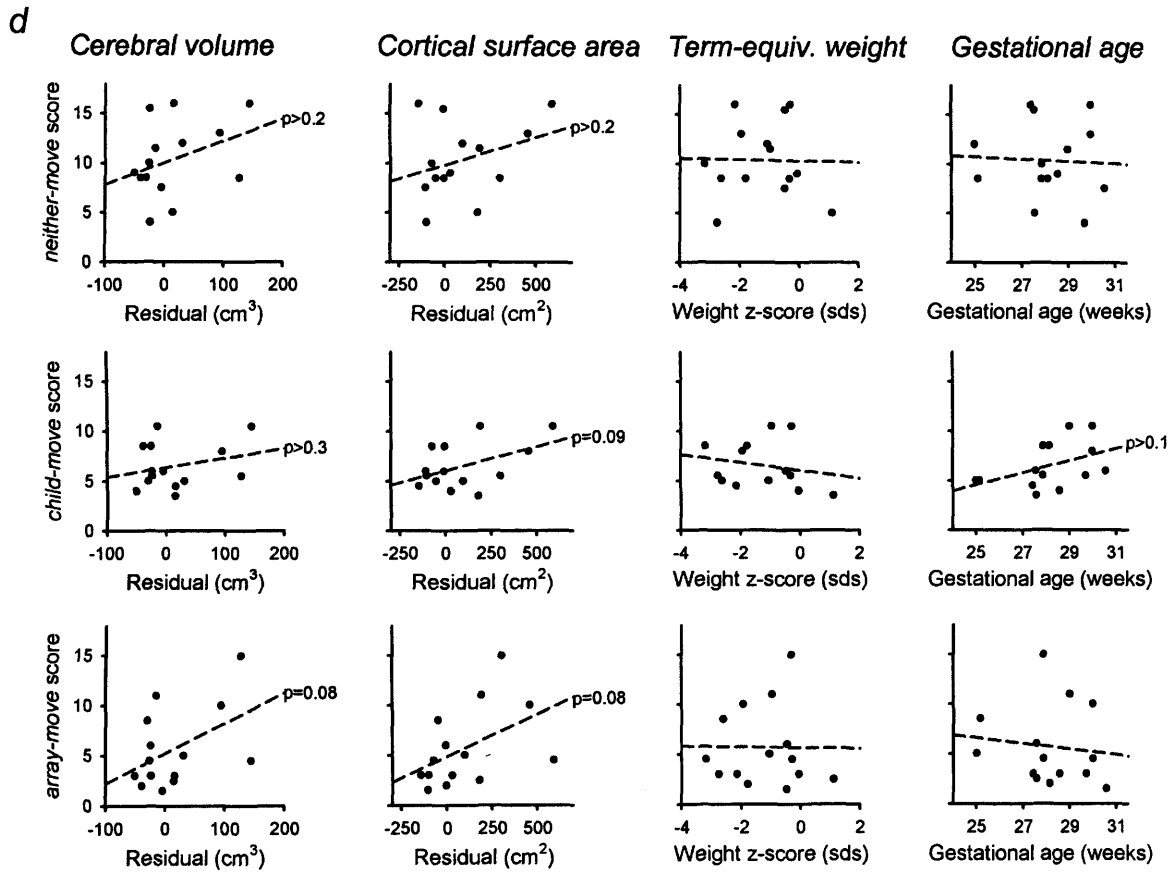

d
Cerebral volume
Cortical surface area
Term-equiv. weight
Gestational age
neither-move score
p>0.2
p>0.2
15
10
5
0
-100 0 100 200
Residual (cm3)
-250 0 250 500
Residual (cm2)
-4 -2 0 2
Weight z-score (sds)
25 27 29 31
Gestational age (weeks)
child-move score
p>0.3
p=0.09
p>0.1
Residual (cm3)
Residual (cm2)
Weight z-score (sds)
Gestational age (weeks)
array-move score
p=0.08
p=0.08
Residual (cm3)
Residual (cm2)
Weight z-score (sds)
Gestational age (weeks)

Figure 29. *(**a-b**) Plots of term-equivalent cerebral volume excluding cerebellum and ventricles (left) and cortical surface area (right). In (**a**) these measures are given against the uncontrolled variable, age at scan. Average volume and surface by age at scan are given by exponential curves fitted to measures from 51 scans in this age range taken at the Hammersmith Hospital (the 14 in this analysis are a subset of these). (**b**) shows each infant's volume and surface converted to a residual with respect to the curve in (**a**) – that is, how far above or below it is an average (premature) scan for that age. (**c**) shows the correlation between the term-equivalent age volume and surface area residuals. In (**d**) these residuals, now on the x-axis, are plotted against scores at six years on the three conditions of the spatial memory task (columns 1 and 2). Correlations with two other potential predictors, body weight at the time of the term-equivalent scan and gestational age, are also shown (columns 3 and 4). A regression line is shown for each correlation; for regressions in the predicted direction the p-value is given. No regression was significant at the 5% level.*

In the cerebral volume ANOVA there was no main effect of *condition* ($p > 0.1$), a significant main effect of *cerebral volume* ($F(1) = 5.27$, $p < 0.05$), and no main effect of *gestational age* ($F(1) = 0.05$, $p>0.8$) or *body weight at scan* ($F(1) = 0.86$, $p > 0.3$). No interaction with *condition* was significant. These results show that total cerebral volume at term-equivalent age predicted spatial memory score at six years, if all conditions are considered together. Such differences as there were between cerebral volume's effect on the different spatial memory conditions were not significant; rather the effect on all three conditions was similar (see **Figure 29**Figure 29 d, column 1). Since total body weight and gestational age were accounted for in this analysis (and were not significant predictors), this measure can be understood to indicate specifically neurodevelopmental factors in later performance, rather than to indirectly indicate development of the whole body.

In the cortical surface area ANOVA there was a nonsignificant main effect of *condition* ($F(2, 9) = 2.02$, $p > 0.1$), a main effect of *surface area* ($F(1) = 9.05$, $p < 0.02$), and no main effect of *gestational age* ($F(1) = 0.30$, $p > 0.5$) or *body weight at scan* ($F(1) = 2.31$, $p > 0.1$). No interaction with *condition* was significant. Therefore like cerebral volume, and ever more strongly so, cortical surface area at term-equivalent age predicted 6-year scores on the spatial memory task as a whole, though not differentially across conditions (see **Figure 29**Figure 29 d, column 2). As in the volume analysis, the effect was not accounted for either by an index of whole-body development (weight at scan) or by gestational age.

Although surface area and volume by term-equivalent age are, on average, reduced in infants who are born more prematurely, variations in brain development within this group must have been such that they accounted for much more of the variance than did the duration of premature exposure to the extra-uterine environment (gestational age at birth). Variations in brain development must also have been sufficiently dissociated from global development that they accounted for much more variance than did whole body weight at the time of the scan.

There was no indication that either volume or cortical surface area predicted some spatial memory conditions more than others. They correlated similarly, though weakly, with each of the three conditions. Furthermore, when entered into ANOVAs, volume and surface area were better predictors of performance than was the *condition* factor (see F-values, above). In other words, term-age brain volume and surface area predicted greater differences in spatial memory scores at six years than did the differences in demands placed on different spatial frames of reference by the three conditions.

The surface area measure, which is the more direct indicator of cortical development, was a somewhat better predictor than the volume measure. This pattern would be consistent with the thesis that the major neural substrate for spatial memory deficits in the premature group was poor cortical (rather than subcortical) development. However subcortical anomalies besides volume reduction would not be detectable on the volume measure, and these have also been shown to predict performance to a degree (see *Results, Qualitative*; p. 146). It can however be concluded that spatial memory impairments have at least a correlate in early cortical development (as indexed by surface area). The volume measure may indicate cortical development as well as subcortical volume and these are not easily distinguishable. In addition, qualitative measures suggest subcortical predictors of performance besides volume.

Discussion

Children born very prematurely showed a deficit in recalling hiding places of objects in the spatial memory task at six years. This deficit was not specific, but corresponded to a delay of approximately one year across all conditions in the task. Few individuals showed strong dissociations between conditions, which would be indicative of a specific impairment.

Correlations with a large set of other developmental tests showed that much of the cognitive or neural basis for recall on the present task was shared with other tasks that had no spatial memory component. These correlations suggest that keeping track of the places of nearby objects recruited a variety of different processes. These varied with the frame of reference that was being used. Ability to use an object-centred or "intrinsic" frame of reference (*array-move* condition) correlated strongly with ability on "frontal" tests of attention and inhibition. This supports the hypothesis of a frontal role in reference-frame selection and/or inhibition on the *array-move* condition. By contrast the baseline *neither-move* condition, in which egocentric representations would suffice, correlated with visuomotor tests, which suggests a posterior parietal component. The *child-move* condition correlated with detection of coherent form (but not coherent motion), a marker test for early visual processing in the dorsal stream (Braddick *et al.*, 2003). This supports the hypothesis that recall after changes of viewpoint produced by walking depends partly on spatial updating with respect to self motion cues, including the visual cue provided by optic flow.

An analysis of qualitative observations from MRI was inconclusive. It is most likely that anomalies seen on these scans have effects on later spatial memory ability, but that the effects are not strong enough to show up reliably in a group of this size. Some indications were that white matter lesions and germinal layer haemorrhages on neonatal MRI, and a thin corpus callosum on six-year MRI, were prognostic of poorer overall ability on the spatial task at six years. However none of these measures was so strongly predictive that it was a sufficient condition for an strong and unambiguous impairment in those subjects who had it. By the same token, premature children who had none of these observations did not perform normally on the spatial memory task, but still showed a considerable delay compared with age matched controls. Overall these qualitative measures seem to be weakly predictive of spatial memory deficits, though their reliability would be likely to improve in a larger group.

The quantitative MRI measures were more strongly predictive of later spatial memory. Both term-equivalent cortical surface area and term-equivalent total cerebral volume predicted spatial memory scores at six years. However both measures predicted performance on the task as a whole, and neither was differential across conditions. Perhaps this is not surprising, as neither measure was localised, but both concerned the development of the whole cortex (in the case of surface area) and the whole brain including cortex (in the case of volume). Of the two measures, cortical surface area was a stronger predictor.

This is consistent with findings of reduced cortical grey matter in premature children (Reiss *et al.*, 2004b), which, when localised using VBM, can be associated directly with specific impairments (Isaacs *et al.*, 2001; Isaacs *et al.*, 2003). It would be very informative to correlate this kind of analysis with impairments on the spatial task, however the quantitative data from the present cohort are not suitable for VBM.

Future analyses should examine the ratio of surface to volume, and the change in this over a series of scans (an approach which has successfully predicted other neurodevelopmental impairments; Ajayi-Obe *et al.*, 2000), once sufficient numbers of children with a series of scans are available for analysis.

Another interesting follow-up with the present task would be with subjects with focal injury that is well-defined from MRI. This would make it possible to test directly the hypotheses about frontal, parietal, and temporal contributions to the task that have been suggested by the present studies.

5.3 Experiment 11

The task from Experiment 10 has also been carried out with a small number of six-year-olds who were born at term but had early focal lesions that can be localised from MR scans. This study, also collaborative with the paediatric neuroimaging group at the Hammersmith Hospital (see Experiment 10, p. 129) is in its early stages. The number of children so far (4) is small, and their lesions have not yet been localised to the level of detail needed to test specific hypotheses, *e.g.* about differential effects of parietal *vs.* temporal lesions on spatial memory. Nevertheless, preliminary results are interesting and suggest stronger dissociations between conditions than were seen in the premature group (Experiment 10).

Children in the group

Children in the group were four six-year-olds (mean age 6.6, s.d. 0.09 years; 1 male) born at normal gestational age. Two had early focal infarcts that involved only the parietal and/or temporal lobes; one had a focal infarct involving only the basal ganglia; one had an infarct involving both the parietal / temporal lobe and basal ganglia. In the case of the three "parietal / temporal" children, the balance of parietal *vs.* temporal and grey vs. white matter involvement is yet to be determined definitively from MRI. Scores on the spatial memory task (see Experiment 10, *Method*; p. 131) were compared with those from 80 typically developing 4-6 year olds from Experiment 10.

Preliminary Results and Discussion

Figure 30Figure 30 plots scores from the four children with focal lesions, alongside scores from the control and premature groups replotted from Experiment 10. Compared with six-year olds in the control group, children with focal lesions scored close to average from the same viewpoint (*neither-move*). However their recall after walking to a new viewpoint (*child-move*) was very low, below average even for age four controls (see Figure 30Figure 30, means and scatter plots). Recall after array rotation (*array-move*) was also quite low, with two of the four children performing at chance (see scatter plots).

An interesting preliminary result is the dissociation between same-viewpoint (*neither-move*) and different viewpoint (*child-move* and *array-move*) recall. Baseline (*neither-move*) recall was close to normal for six year olds. *Child-move* showed a delay of two years or more. The *Array-move* delay was greater than one year, but can be

characterised less accurately as the earliest control data is from age five (see Figure 30Figure 30). This pattern was not matched by any control group aged four to six. It is also unlike the premature pattern, which closely matched the pattern for controls a year younger.

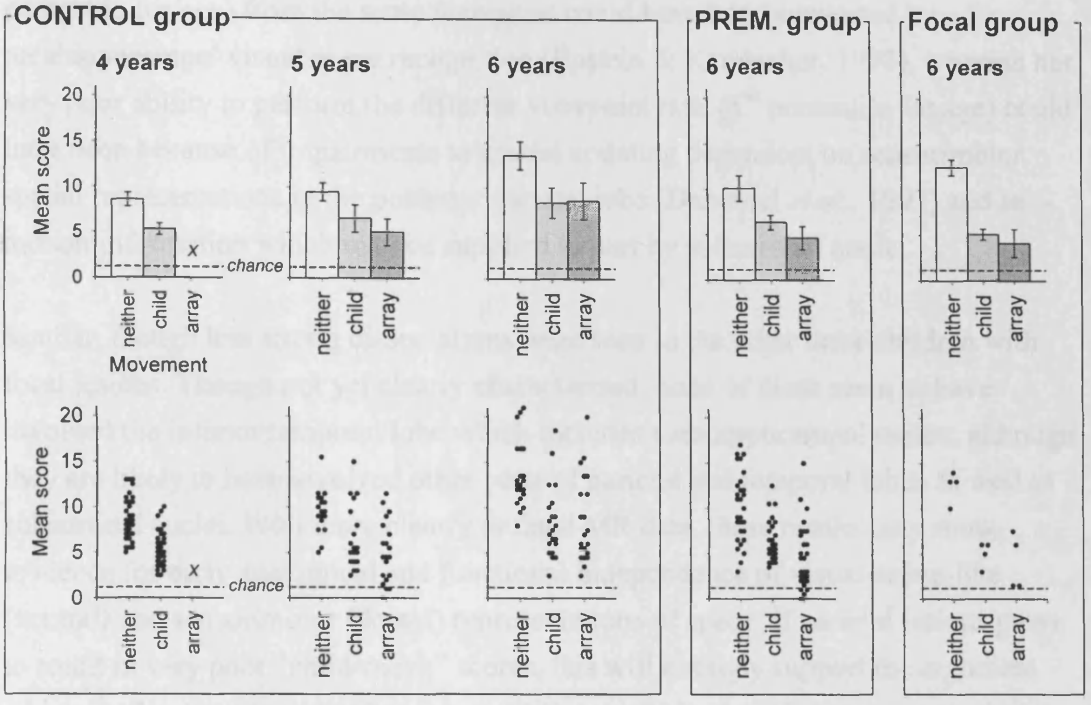


Figure 30. Scores from the four children with focal lesions (right), with control (left) and premature (middle) scores from Experiment 10.

Differences between conditions in individual children were also calculated and compared with differences in individual children the control group, as in Experiment 10 (*Results / Dissociations in individual children*; p. 140). One child (25%) had a difference between *neither-move* and *child-move* that was in the top 5% of control-group difference scores. That is, this child showed a dissociation between a high same-viewpoint score (14) and a low score after walking to a new viewpoint (3.5) so great that it was seen in less than 5% of controls. Her score from the same viewpoint would place her at the 71st percentile for a six-year old, whereas her score after walking to a different viewpoint was below the 5th percentile. This child had a large left sided middle cerebral artery (MCA) infarct which had resulted in a hemiplegia. The infarct involved the parieto-temporal region as well as the basal ganglia, the internal capsule and the thalamus.

The middle cerebral artery passes by the parieto-temporal border (the sylvian fissure), and MCA infarcts therefore often involve parts of both parietal and temporal lobe. However inferior parts of temporal lobe are unlikely to be affected. In the case of the child with an MCA infarct and a same viewpoint – different viewpoint dissociation, the parahippocampal cortex is likely to have been spared. Her excellent recall (71st percentile for age) from the same viewpoint could have been supported by parahippocampal visual scene recognition (Epstein & Kanwisher, 1998), whereas her very poor ability to perform the different viewpoint task (5th percentile for age) could have been because of impairments to spatial updating dependent on sensorimotor spatial representations in the posterior parietal lobe (Duhamel *et al.*, 1997) and self-motion information which may be supplied in part by subcortical nuclei.

Similar, though less strong dissociations were seen in the other three children with focal lesions. Though not yet clearly characterised, none of these seem to have involved the inferior temporal lobe which includes parahippocampal cortex, although they are likely to have involved other parts of parietal and temporal lobes as well as subcortical nuclei. With more clearly defined MR data, these results may show evidence for early anatomical and functional independence of visual-scene-like (ventral) and sensorimotor (dorsal) representations of space. If parietal lesions prove to result in very poor "child-move" scores, this will strongly support the argument which has been made so far that this condition taps into dorsal-stream processing.

5.4 Atypical development: conclusions

Experiments 9 – 11 studied the development of spatial frames of reference in individuals with Williams Syndrome (WS), children born very prematurely, and a small group of children with focal lesions. In each case a pattern of deficits was identified. Adults with WS showed normal and additive use of body- and room-based frames of reference, but only marginal use of an object-centred frame. In this respect they very closely matched typical four year olds. It was suggested that this deficit might depend on global neurodevelopmental factors and/or frontal-lobe anomalies. Children with WS showed an unusual pattern which may represent a dominance of ventral-stream spatial representations over dorsal, or might correspond to a pattern usual for control ages below three years. Results from both adults and children showed very substantial delays in spatial representation in Williams Syndrome, consistent with their other reported visuospatial difficulties.

Six-year-olds who had been born very prematurely had a global impairment corresponding to a delay of around one year, but were not as a group impaired in their use of some spatial frames of reference more than others. Qualitative and quantitative MRI found some predictors of global performance, but no predictors of ability to use specific frames of reference. As the MRI data was not localised it is perhaps unsurprising that only global factors were seen. Correlations with a large number of other developmental tests suggested some interesting dissociations between the bases for the spatial frames tested on the task. It was suggested that viewpoint-independent recall when the array conflicted with room- and body-centred frames of reference had a frontal component, recall from the same viewpoint had a posterior parietal component, and recall after walking to a new viewpoint had a visual dorsal-stream component related to the accurate processing of optic flow.

Results from a small group of six-year-olds with focal lesions provide preliminary evidence that neural correlates for spatial frames of reference are dissociable and anatomically specific in early development. In particular, ventral-stream (parahippocampal) representations of visual scenes may be functionally dissociated from dorsal-stream (posterior parietal) representations of nearby objects, so that early injury to the latter network can leave the former functioning normally. Excellent same-viewpoint recall in a child with a large MCA infarct, who had a hemiplegia and performed poorly on motor tests as well as verbal tests and tests of attention supports the thesis that viewpoint-independent representations of scenes rely on specific mechanisms and are dissociable from other spatial and cognitive abilities.

These results should be followed up with detailed analysis of these children's MRI data, and with more participants with focal lesions that can be well characterised. A comparison between parietal, inferior temporal, and frontal lesions would be very informative. It would also be very useful to test individuals with hippocampal pathology, as in the present task it has not yet been possible to determine the role of the hippocampus either in using either distal landmarks (landmarks in the testing room which stay consistent when the array does not rotate), or using the smaller configuration of landmarks within the array. It has been suggested that substrates for the ability to use landmarks within the array are frontal and hippocampal, but the balance of these is unknown.

CHAPTER 6

General discussion

6.1 Summary of findings

The starting questions for this thesis were: how is spatial information represented in the developing human brain, and how are different representations combined or transformed to solve particular spatial problems? The theoretical background came from two fields. First, recent models of spatial representation derived from behavioural, neuroimaging and neurorecording studies with humans and other mammals, which suggest that spatial representations depend on a network of specialised mechanisms that normally interact but can be dissociated experimentally. Second, classic findings from the developmental literature, which suggest that the development of spatial representation follows a sequence of stages in which children make specific systematic errors. The approach in this thesis was to seek to explain these developmental patterns of error using the framework of dissociable components made available by the adult / animal model.

The main tactic therefore was to probe behaviourally for developmental dissociations between representations whose neural bases are thought to be distinct. This made it possible to test a powerful explanation of the developmental phenomena: that children's systematic errors result from differences in the developmental trajectories of different neural substrates for spatial representation. This approach was extended to probe for systematic errors in clinical groups whose potentially anomalous brain development could be characterised to some degree.

In the first set of studies, the behavioural immaturity was the reported inability of children aged 18 – 24 months (and adults performing an interference task) to use a combination of a coloured indirect landmark and the shape of the room to find a hidden object. These subjects were reported to use room shape, but to ignore the coloured landmark. It was previously argued that their reorientation therefore depended on a dedicated "module" which cannot process colour (Hermer & Spelke, 1994; Hermer & Spelke, 1996), and that the emergence of flexible reorientation depended on spatial representations expressed in language (Hermer-Vazquez *et al.*, 1999; Hermer-Vazquez *et al.*, 2001).

Initial studies with adults (Chapter 2) helped to narrow down the role of motor planning in the task. Disoriented subjects' search actions in the enclosure were partly driven by a (typically erroneous) sense of direction. It was suggested that the design of the original enclosure was biased in that it made it easier to reconcile the directional sense with geometry, than with colour.

Results from these experiments could not however be related directly to the original phenomenon, the disregard of colour in adults performing a concurrent verbal task, since this was not successfully replicated, except in one subgroup of naïve subjects in one experiment. A subsequent study has shown that the interference effect is not specific to language tasks, but is specific to naïve subjects who were not instructed on what the task inside the enclosure would be (Ratliff & Newcombe, 2005). It can be concluded that the adults in the Chapter 2 studies were too carefully instructed to replicate the effect.

The following experiments (Chapter 3) tested disoriented 18 – 24 month olds with an enclosure modified to increase participants' chances of using flat coloured walls as landmarks. Successful use of these landmarks would argue against Spelke's thesis that disoriented search at this age depends on a "geometric module" encapsulated with respect to colour. Walls were also progressively enriched with colours, textures, and recognisable shapes across conditions, to evaluate whether providing additional "feature" information would increase its use for search.

In a square enclosure, 18 – 24 month olds *did* search using indirect flat coloured walls. This shows, contrary to the "geometric module" thesis, that there was not an in-principle inability to resolve orientation using colour at this age. Nevertheless it seemed that colour was less favoured than room shape at this age, as children used colour less regularly in these studies than they had previously used geometry.

Enriching the landmarks (coloured walls) with additional colours, textures, and recognisable objects, did not facilitate their use at all. However changing the stimuli so that different recognisable pictures were close to the different corners (*i.e.* the stimuli were no longer symmetric about the centre of each wall) did facilitate performance. The first result shows that in this task, children's use of flat colour and texture for action is limited irrespective of how much colour *etc.* is provided (within the bounds tested). The second result shows that part of children's difficulty was in combining these indirect landmarks with left-right discriminations. This argues against an in-principle limit on the use of flat colours and shapes for disoriented search at 18-24 months, but shows that part of the difficulty is in resolving their laterality.

It was concluded that further experiments should test for the generality of the "disregard of colour" effect, by seeing whether it arises in other circumstances, particularly without disorientation. This would show whether the effect might depend on general principles in early visual cognition, which could be linked to current

models from neuroscience. Theoretical frameworks that could be brought to bear on the problem include dual-systems models of visual processing (Ungerleider & Mishkin, 1982; Milner & Goodale, 1995) and recent restatements of these (Glover, 2004). An initial experiment was proposed (p. 78) which would test the hypothesis that 18-24 month olds' disregard of colour could be understood as an "action / perception" dissociation.

In the following experiments (Chapter 4), the behavioural starting point was the reported poor use of reference frames provided by external landmarks, compared with those provided by the self, in young children. These studies traced the emergence of different spatial frames of reference over the age range 3 – 6 years, using a hidden toy retrieval task with an array of hiding places bordered by landmarks. A theoretical framework for understanding changes in the use of spatial frames of reference was provided by adult and animal models, which identify body-based spatial representations updated with movement (path integration) with the posterior parietal lobe, body-based representations corresponding to a static viewpoint with the inferior temporal lobe (parahippocampal cortex), and externally referenced representations using landmarks with the hippocampus.

When the array was consistent with the room, recall could be based on room landmarks as well as on body-based representations updated with path integration. When the array was consistent with the body, static encodings of the visual scene could be used. When the array was consistent with neither body nor room, children had to use local landmarks within the array. Use of this "intrinsic" frame of reference was hypothesised to depend on the hippocampus, and possibly to have an additional frontal-lobe component corresponding to selection and inhibition of reference frames.

The first result was highly reliable and dominant use of a reference frame defined by the room, and not the body, as early as three years. When the hidden toy's position within the room conflicted with its position with respect to the body, three year olds searched according to its position in the room. The room exerted a much greater influence on search than body even when the array of hiding places was rotated so that the egocentric positions of the toy was matched at retrieval and test. Unlike "egocentric" 6 - 9 month olds, reported to search only using the body frame of reference, three year olds in this study had a strong awareness of objects' positions in external space.

The second result was that although the room frame of reference was dominant, keeping the toy consistent with the *body* between retrieval and test also produced

reliable recall advantages, which were additive with the advantages for room consistency. This parallels the adult pattern (Wang & Simons, 1999). These results suggest that spatial memory in this early age range already depends on separable, additive, components.

Awareness of the toy's position within the room is consistent with posterior parietal representations updated with self motion, and with hippocampal representations using landmarks. Awareness of its position with respect to the body is consistent with viewpoint-dependent representations of scenes in the temporal lobe. The initially greater weighting of the room-consistent representations for action is consistent with their closer link to parietal motor planning.

The third result was the emergence, at five years, of viewpoint-independent recall based only on landmarks within the array, and not on either body or room. This ability depended on object-centred or "intrinsic" representations. This most demanding and last-developing ability may depend on the frontal lobes and / or the hippocampus. The "frontal" component of the task could correspond to selecting the correct (intrinsic) frame of reference, and inhibiting the incorrect (body and room) frames.

Taken together, these results show behavioural markers for the emergence of components of spatial memory thought to be neurally dissociable. An interesting further application of the task was to the assessment of spatial frames of reference in three clinical groups.

In individuals with Williams Syndrome (WS), who show severe visuospatial difficulties, the adult pattern of performance very closely matched that of typical four year olds (Chapter 5, Experiment 9). That is, individuals with WS showed a strong awareness of the hidden object's place within the room, an additional (and additive) awareness of its position relative to the body, but only a marginal awareness of its position within the array. This can be interpreted in two ways. It can be said that visuospatial impairments in WS correspond to the near-absence of one kind of representation in particular: object-referenced representations. However since these are the last to emerge in normal development, this "specific impairment" can also be described as a severe global developmental delay, where spatial frames of reference in adults with WS on average do not develop beyond the typical 4 year old level. Children aged 8 - 15 years with WS showed an unusual pattern, in which the room was less dominant than either in adults with WS or in controls aged 3 – 6 years. This pattern, consistent with a preference for "ventral" representations in WS, may correspond to a normal pattern for an age below three years.

In Experiment 10 a group of children born very premature (gestational age 25 – 30 weeks) was tested on a further version of the task, which was made suitable for individual assessment so that individual spatial memory results could be correlated with individual MRI data. The imaging data however did not make it possible to test explicitly for developmental structure-function relationships, as it was not cortically localised, but related either to widespread qualitative anomalies or to whole-brain quantitative measures of volume and surface area.

As a group, premature children showed a delay of around a year on use of each of the spatial frames of reference tested, but not a differential pattern of delays. Quantitative measures of brain development predicted deficits on all conditions rather than on particular conditions. The most predictive measure was cortical surface area at term-equivalent age, suggesting that the major substrate for later spatial impairments in children born very premature was reduced cortical growth, rather than non-cortical anomalies (*e.g.* of white matter or ventricles), which were less strongly predictive. Correlations with a large number of other developmental tests suggested some interesting dissociations between the bases for the spatial frames tested on the task. Retrieval using only array landmarks (requiring object-centred or "intrinsic" representations) correlated strongly with "frontal" tests of executive control and inhibition, whereas retrieval using body or room referenced representations correlated with motoric or "parietal" tests. This supports the thesis that object-centred representations depend partly on the frontal lobes, whereas body and room referenced representations depend on the parietal and temporal lobes. The very poor use of the object-centred reference frame in adults with Williams Syndrome suggests that their large delay on the task may be due to poor frontal development.

Preliminary results from six-year-olds with early focal lesions (Experiment 11) suggest that neural correlates for different spatial frames of reference are indeed dissociable. In particular, representations of visual scenes may be functionally dissociated from sensorimotor (movement-updated) representations of nearby objects. This supports the adult / animal neuroanatomical model. It also suggests that for representations of space, functional specialisation happens early in development, and possibilities for later recovery of function are limited. In particular, early injury to posterior parietal cortex means that dorsal-stream (sensorimotor) spatial representations develop poorly. These parietal functions are not successfully compensated for by spatial representations in the ventral stream and parahippocampal cortex. This would be consistent with the dorsal-ventral dissociations seen in adult neurological patients (Milner & Goodale, 1995).

6.2 Components of spatial representation: a developmental model?

These studies have behaviourally dissociated some representations whose neural basis is thought to be distinct, and found developmental patterns that can be interpreted in terms of differences in the developmental trajectories for various neural substrates for spatial representation. The present findings fill in several gaps in an emerging model of the development of spatial memory. Age ranges and tasks to which these findings directly apply are limited. Nevertheless it is possible to extrapolate from the present findings in several interesting directions.

The self in the world: a developmental sequence

Results from the "town square" task (Experiment 7) bear in an interesting way on the Piagetian question: how do children overcome their "egocentrism" and become aware of their place in the world? This study found an important developmental change at three to six years, a good while after the classic "egocentric" period (the first year). Three year olds' memory for location was very strongly guided by their sense of place within the external framework defined by the room. They relied on purely egocentric representations much less. Crucially, when an egocentric solution was available that conflicted with the room (*both-move*), 3 year olds searched with respect to the room and so failed the task, whereas an "egocentric" 6 month old would be expected to succeed. It was not until age five that children overcame the dominant external frame of reference, having begun to use object-referenced representations.

Putting this sequence together with the classic early "egocentric" period, it is apparent that the developmental trajectory for the young child's reliance on the stable, permanent frame of reference provided by the external world is U-shaped, in that it emerges, peaks, and recedes again (producing an "upside-down U" shape). Thus for much of the first year the child seems not to be aware of a stable external spatial framework, and relies only on the body for spatial coding. However by three years the child has become so strongly aware of the framework of external space that he bases representations most strongly on it. This is the apex of the "upside-down U". But by five years a further refinement is added: reference frames defined by individual moveable objects in the world can be processed separately, and the larger and more stable framework can be inhibited when necessary; the external framework is no longer totally dominant. It would be very interesting to confirm a U-shaped trajectory

for use of external frames of reference by testing the entire age range from 6 months to 5 years on a single scaleable task.

Specialised representations and binding

The "blue wall" and "town square" tasks both tested ways in which children combined specialised representations to solve spatial problems. When frames of reference in the "town square" conflicted, correct solutions depended on choosing the right frame of reference (Experiments 7 - 11). When they did not conflict, combining representations provided by different frames of reference would be the strongest basis for retrieval. Indeed there was evidence that children across the age range combined body- and room-based representations additively in this way. Similarly, when children were disoriented in the "blue wall" enclosure, finding the object depended on combining representations of colour, texture and shape with representations of own orientation, room shape and laterality.

In each of these cases the suggestion is that different aspects of the same perceptual input are processed in parallel by mechanisms specialised to process those aspects in particular. For example, in children aged 5 years and above, the retinal projection of the spatial array in the "town square" task (Experiment 7) leads both to a viewpoint-specific "visual snapshot", and to a viewpoint-invariant representation of the overall layout of the landmarks. These representations are then recombined to guide a response - for example, in the "town square" task, visual snapshots and allocentric representations combine additively to improve recall accuracy.

The first part of this model is the more extensively researched. There are well-developed accounts of how partly-overlapping hierarchies of neurons could use simple, local rules, to transform an initial input, autonomously and in parallel, into a set of different representations. The second part is more difficult. What does it mean to say that these representations are recombined or integrated to drive a response? One framework is provided by computational models of the organisation of neural information processing in the network of areas concerned with navigation, including the hippocampus, parahippocampal and posterior parietal cortices, and "head direction cells". These models (*e.g.*, McNaughton *et al.*, 1995; Becker & Burgess, 2001) specify the reciprocal interconnections between egocentric codings of local vectors, the sense of orientation, self-motion information, visual landmarks, and an environment-centred "map". Gathering behavioural (rather than neurophysiological) evidence that can discriminate between different versions of these neural models is very challenging, and developmental behavioural data capable of discriminating

between different developmental versions of a model even more so. Nevertheless, detailed quantitative data of the kind collected in Experiment 7 might be capable of being shown mathematically to support some kinds of models or rule out others.

Data from the present studies suggest several features of the early integration of different representations of space. At 18-24 months, the integration of coloured visual landmarks with angular and heading information was possible, but was subject to a low threshold, above which adding further visual features to the landmarks did not improve performance (Experiment 5). This initial result constrains accounts of how these sources of information might be combined. The difficulty seems not to be insufficient saliency of the landmark, but a low capacity for use of this category of visual information for action inside the enclosure.

Between three and six years there were important developmental changes in the use of spatial frames of reference, however different reference frames were combined in a similar additive pattern across the age range (Experiment 7). This suggests that whereas representational systems supporting different frames of reference were still developing, some processes for their integration for action were more or less mature. Was the locus of developmental change therefore at the representations, but not at the final integration function? Unfortunately the data are not able to answer this. Use of the late-emerging "intrinsic" (array-centred) frame of reference depended on inhibiting the conflicting body and room frames. From behaviour it cannot be known how much earlier "intrinsic" representations might have been present, but not selected for action (Experiment 7, *Discussion*). This returns to a point raised at the end of Chapter 1. Those representations that are detected behaviourally may be a restricted subset of an organism's neural encodings of space, the rest being undetectable behaviourally because they have been inhibited or not selected. A behavioural analysis of representations of space may have to be content with a level of description that deals with final selected responses.

A further kind of visuospatial binding not addressed in the present studies (except for the pilot virtual "town square"; Experiment 6) was the maintenance in memory of several different targets whose identities must be kept distinct. In the second version of the real "town square" (Experiments 10 - 11), in which children had to remember more than one object, the objects were kept identical so that this additional demand was not added to the task. However keeping track of the places of different objects without confusing them is a fundamental demand for spatial cognition. A related everyday demand in which different places must be given distinct "markers" is remembering which of a series of places has already been visited (*i.e.* foraging;

Gilchrist, North, & Hood, 2001). The development of bindings between identities and places should be tested in follow-up studies. A potential difficulty is in scoring searches to distinguish place errors from identity errors. A good task would provide independent measures of location accuracy, identity accuracy, and accuracy for conjunctions of location and identity. Such a task could show developmental trajectories for the binding of these kinds of information, as distinct from processing of each kind alone.

Space, language, and domain specificity

An important question raised by both studies was the interdependence of spatial representations and other cognitive abilities. The background to the "blue wall" task was Spelke's thesis that the ability to combine colour and room geometry depended on the development of language. Successful use of colour in disoriented 18-24 month olds (experiments 5 - 6) argues against this. There was also no evidence for a crucial role for language in solving viewpoint-independent recall on the "town square" (Experiment 7). Those five and six year olds who lacked the terms to describe a hiding place in relation to landmarks were still able to find places in the array using only such landmarks.

For older subjects however, space and language were closely linked. Adults faced with the same "town square" task overwhelmingly chose to use a verbal strategy when one was available, and those precluded from using a verbal strategy performed less well (Experiment 8). For some kinds of spatial tasks, language must provide a representational framework more robust than non-linguistic codings of angle and distance. Much work is needed to separate clearly linguistic and non-linguistic contributions to different spatial tasks. It is clear that landmark tasks such as the "blue wall" and the "town square" lend themselves well to verbal strategies. The hiding place might be "left of the blue wall" or "in front of the post office". On the other hand, for a task in which subjects did not have to remember where an object was, but had to keep track of own position (for example, while homing without vision), it is hard to see much of a role for language.

Individuals with Williams Syndrome typically show an interesting disjunction between poor visuospatial and relatively good linguistic abilities. However in the present studies, those adults with WS who had a high verbal (vocabulary) age were no better on the "town square" than were those with low verbal age (Experiment 9). There was also little evidence that adults with WS used language to solve viewpoint-independent recall, in the way that typical adults did. Were individuals with WS

incapable of representing the requisite spatial relations in language, or did they just fail to think of this strategy? Observations in Experiment 9 suggested the latter. Although most subjects with WS did not themselves think to use a verbal strategy, they could nevertheless use one to support viewpoint-independent recall, once it was suggested to them. This interesting result highlights a further consideration in assessing individuals' use of different representations: failure to choose a representational strategy spontaneously cannot always be interpreted as inability to use it. In the case of Williams Syndrome, explicit training in verbal strategies might provide a helpful shortcut to everyday tasks involving spatial memory.

Correlations of "town square" performance with an extensive set of standard developmental tests in the premature group (Experiment 10) provided further data on domain specificity in early spatial memory. There were strong correlations between "town square" conditions and many developmental tests which have no spatial memory demand. This suggests that performance on the spatial memory task did not depend only on specific, encapsulated processes, but called on cognitive resources shared with other tasks – including, for example, attention and inhibition in the *array-move* condition, and perception of coherent motion (which may relate to processing of optic flow) in *child-move*. Differential correlations also showed that cognitive substrates for the "town square" task were not the same across conditions, but varied from condition to condition. This is consistent with the neurophysiological model sketched in Chapter 1. Use of different reference frames depended on different, only partly overlapping mechanisms. Many underlying processes are clearly not task-specific to spatial coding. A clear example of this was the "frontal" contribution to selecting frames of reference on the *array-move* condition.

It would be good if these distinct cognitive substrates for different spatial frames of reference could be confirmed to have dissociable neural bases in development. However the clinical groups (experiments 6, 9, 10, 11) have not yet provided clear data suitable for assessing structure-function relationships. A promising avenue for future research is the focal lesion group (Experiment 11), who have specific patterns of early injury that can in future be localised accurately from existing MR images. Further possibilities are neuroimaging or neurorecording. Of these methods, evoked potential measures would be the most suitable for the age range studied here, three to six years, over which major changes in use of spatial frames of reference took place.

It is reasonable to hypothesise that use of the same frames of reference would recruit the same apparatus in children as it does in adults. The neurodevelopmental and cognitive consequences of early injury however are less easy to predict, since

plasticity in development means that some functions can be successfully remapped by adjacent regions of cortex or by the other hemisphere. A question for further studies is how these processes work for regions involved in spatial representation. Preliminary indications from children with focal lesions (Experiment 11) are that parietal-lobe spatial functions cannot be remapped after injury, even if the injury occurs very early.

Larger spaces and longer memory spans

In line with the strategy set out in Chapter 1, the present studies were carried out in carefully controlled environments, where spatial cues available for subjects to use were wholly specified (the virtual and real "blue wall" enclosures; Chapter 2 and 3), or almost wholly specified (the "town square", Chapters 4 and 5, where visual cues in the larger testing room were uncontrolled). These designs enabled clear conclusions to be drawn about the perceptual and cognitive bases for children's abilities to solve each task. However since both experimental environments were small in scale, required short retention intervals, and were completely novel to the subjects, they tested children's spatial memory only within these parameters. Much of everyday spatial memory and navigation depends on large spaces, long retention intervals, and incremental learning.

Size and interval in these studies were driven by practical demands. A small cue-controlled space is much more easily constructed than a large space. In adult studies virtual environments have been used to good effect (*e.g.*, Hartley *et al.*, 2003); however a non-immersive virtual environment (Experiment 6) was not comprehensible to young children. Tests to check for retention after a long interval are possible to arrange, but potentially time consuming. For example, collecting data from sixteen independent hiding events per child (Experiment 7) would be a daunting undertaking if there was a delay of a week between each event. For these reasons small spaces and short retention intervals were natural starting points, however the tasks used in these studies could be expanded in size or time scale.

Lack of familiarity presents a different problem, as testing each individual in an environment they knew well would introduce variability between environments, and it would then be hard to carry out the kinds of detailed quantitative analyses pursued in the "town square" tasks (experiments 7 - 11). Familiarising children over a long period with a controlled (experimental) space would be difficult to arrange. However familiarity is likely to be an important factor in recall. If hiding places were not in the novel "town square", but in a highly familiar space such as the child's living room, it may well have been easier to recall them. Studies of this kind have found excellent

recall for objects hidden in well-known "natural locations" at an early age (*e.g.*, at 18-30 months; DeLoache & Brown, 1979). In the present studies, both tasks were really tests of whether children could *rapidly* learn to use a novel set of visual landmarks to find hidden objects.

How well might components of spatial memory identified in these small, short, rapid-learning tasks map onto those used for more complex navigation in larges spaces? If three-year-olds use both body- and environment-based representations in such tasks (*i.e.* Experiment 7), they can probably also use both for more navigational tasks in larger spaces. Thus they would probably know how to find a place both egocentrically ("turn left at x"), and allocentrically ("it's opposite y"). When the egocentric frame of reference was available (*i.e.* if they were coming from their usual direction) they should remember the way better than from a novel direction, where only an allocentric coding was available. These are reasonable suppositions, but in large-scale navigation the relative weighting of these different representations may well differ from the weighting in the "town square". However in a large space it is much more difficult to carry out equivalents of all the "town square" manipulations, particularly putting the entire visual space at odds with path integration (*i.e.*, rotating the environment while the subjects stays still).

One way to achieve this would be to adapt a homing paradigm from the rodent literature, in which illuminated landmarks are rotated while the subject is in the centre of a sparse circular enclosure (Etienne *et al.*, 1990). In such a task it is possible to assess the contributions of self-motion information (predicting a correct homing path) and visual landmarks (predicting a homing path shifted by the magnitude of the landmarks' rotation). Comparing these conflict conditions with homing without landmarks (using self-motion information only), and homing with stable landmarks, could provide detailed developmental trajectories for the integration of these sources of spatial information. Proprioceptive and motoric self-motion cues could further be dissociated from visual cues (optic flow) by enhancing or reducing textures providing optic flow, or reducing motoric information by moving subjects passively.

Conclusions

These developmental studies used a framework of dissociable components to understand the development of spatial memory. Developmental trajectories were quantified for children's use of different spatial frames of reference. Differences in these trajectories can be understood to depend on different rates of maturation in the

neural substrates for spatial representation. Preliminary evidence that in development, the cognitive and anatomical basis for different representations is indeed separate came from studies with clinical groups.

Three main directions have been suggested for future studies. First, a test for further immaturities in combining different kinds of visual information outside the blue wall enclosure. Second, independently tracing developmental trajectories for object identity memory, place memory, and bindings between these. Third, studying the development of interactions between spatial representations driven by self-motion (path integration) and those based on external landmarks using an arena in which landmarks are rotated to conflict with path integration.

Appendices

Appendix 1: Pilot studies 1 and 2

A1.1 Pilot study 1

The purpose of this pilot study was to devise the virtual environment and to check that normal adult performance (without shadowing) could be replicated in this space when it was presented on a computer monitor. Changing the participant's simulated facing direction between presentation and test was the virtual equivalent of disorientation. When all four walls were white, making the room ambiguous, the question was whether subjects would use the virtual room's geometry to search. When the disambiguating blue wall was present, the question was whether they would use this additional colour cue. After 30 seconds of disorientation by turning, adults who were not carrying out a concurrent verbal task had no problem using both geometric and colour cues in a real space (Hermer-Vazquez *et al.*, 1999).

Method

Subjects

Subjects were 20 paid volunteers and graduate students at the Department of Psychology, University College London (10 male), aged 19-50 with mean age 29.5 (s.d. 8.2) years.

Apparatus

A testing room of dimensions 169 x 123 x 185 cm, as described by Hermer-Vazquez *et al.* (1999), was presented from the first-person perspective on a monitor with resolution 1280 x 1024 (see Figure 31). Subjects sat at 35cm, from which distance screen width subtended 55° visual angle; the environment was rendered with 65° visual angle. Subjects' virtual positions were locked to the centre of the virtual room. A mouse was used to rotate, to change vertical viewing angle (pitch) and to initiate searches.

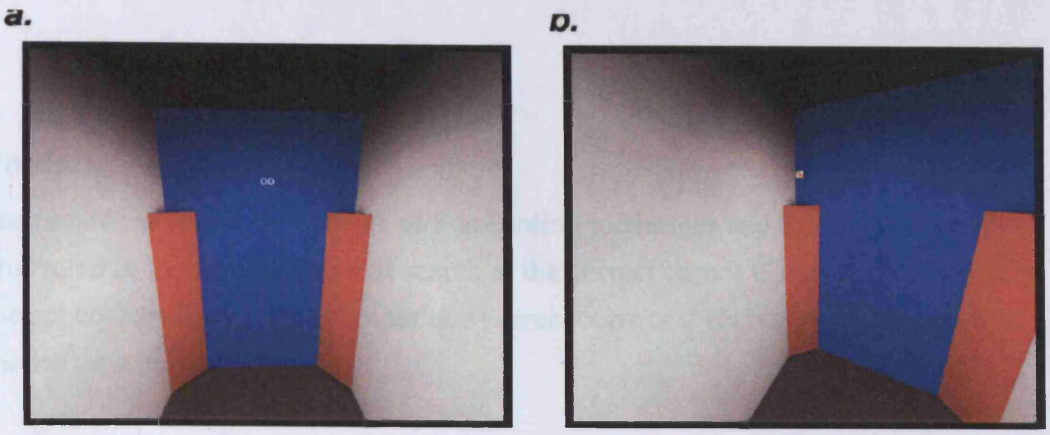


Figure 31. *Example views in the virtual room.* ***a****, facing the blue wall, with superimposed "look" cue instructing the subject to look around the room.* ***b****, hiding event, a block descending behind a panel.*

Design

Participants completed 12 trials with four white walls, and 12 with three white walls and one blue wall. As in the original studies, one of the two shorter walls was blue in the latter condition. Half of participants and half of males experienced the all-white condition first. Walls faced initially and after disorientation followed a pseudo-random sequence in which every wall was faced an equal number of times in each condition. Hiding locations were randomised in blocks of 4, each block including all 4 locations, and no block beginning with the location on which the last ended.

Procedure

In the familiarisation phase, participants learned to use the mouse and to follow onscreen instructions in a landmark rich space that did not resemble the testing room. Once they were confident with the different on-screen instructions and mouse controls, the experiment began.

Each trial began with the subject facing one of the walls. Participants were prompted to use the mouse to look around the room. An arrow then prompted them to turn towards one of the corners. Once the corner was in view the hiding event took place. A rotating cube appeared above the panel and descended out of view. The screen turned dark and subjects fixated a central cross for 30 seconds, the duration of the original disorientation procedure. The room reappeared with the view changed so that participants found themselves facing a pseudo-randomly predetermined wall, and used the mouse to rotate and initiate a search at one of the corners. Visual feedback was given: the cube reappeared on successful trials, and an "X" appeared on unsuccessful trials.

Analysis

Each search was coded, C, N, R or F according to Hermer and Spelke's scheme, illustrated in Figure 32. Rates of search at the correct corner C and at geometrically correct corners C+R, and at colour cue correct corners C+N were compared with chance on a binomial test.

Hiding place ***Possible search locations***

"Geometrically correct": C + R
"Colour correct": C + N

Figure 32. *Coding scheme for searches. Left: example trial on which the object is hidden in the corner marked "*".Right: coding for each of the four possible search locations. C: correct; R: rotational equivalent; N: near corner; F: far corner. C and R searches are "geometrically correct" as the geometry cue matches. C and N searches are "colour correct" as both bear the same relation to wall colour (both are either at a white-blue corner, as in this example, or at a white-white corner). In the room with four white walls the C+N ("colour correct") measure is not meaningful.*

Results

Figure 33 shows rates of search alongside previous results from a real environment.

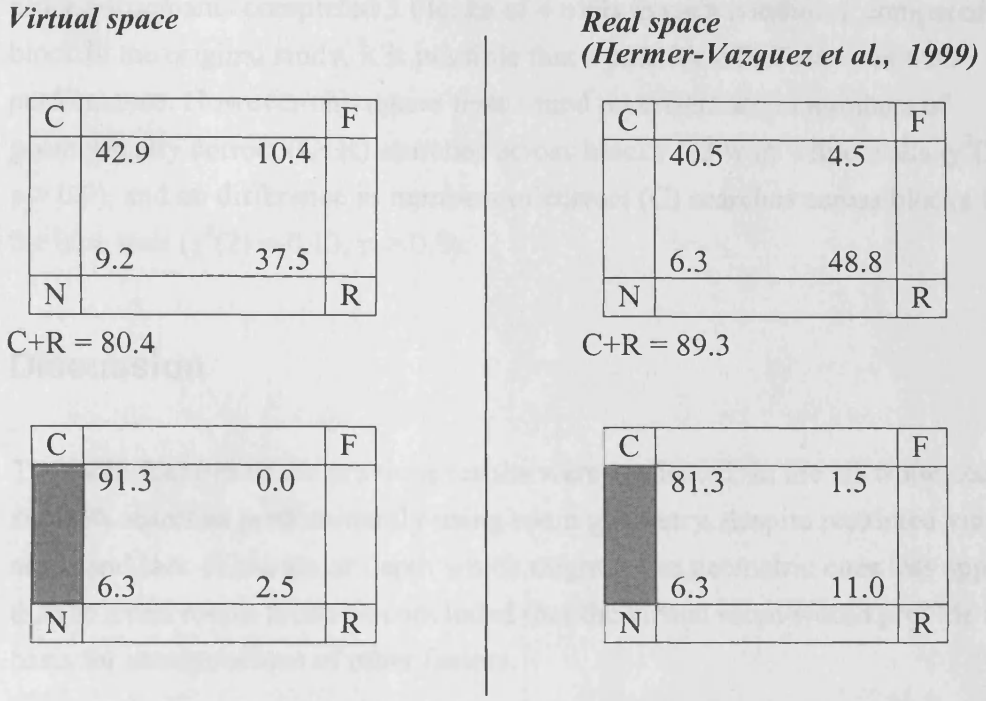


Figure 33. *Rates of search (%) on the virtual task (left), compared with previous results on the real task (right) for the white room (top) and blue wall (bottom) conditions. For the white room, searches at the visually identical C and R corners are summed to give the rate of "geometrically correct" search.*

When no disambiguating colour cue was available (Figure 33, top), participants in the virtual space searched at "geometrically correct" corners C and R on 193 of 240 (81.3%) trials. This rate was well above the 50% expected by chance (binomial $p < 0.001$). This result shows that participants used the cue provided by the virtual room's rectangular shape.

When the disambiguating blue wall was available (Figure 33, bottom), participants used the conjunction of colour and geometry to find the object on 219 of 240 (91.3%) trials, a rate likewise well above the 25% expected by chance (binomial $p < 0.001$).

These rates were similar to those recorded in the real environment (Figure 33, right). The rate of "geometrically correct" C+R search in the virtual all-white room was

slightly lower than in the previous study. This suggests that the geometric cue may have been less apparent on the screen than in a real room. By contrast, the rate of correct (C) search in the virtual "blue wall" room was slightly higher than it had been in the real room. This is consistent with an advantage for participants who have not been physically disoriented by turning.

Since participants completed 3 blocks of 4 trials in each condition, compared with one block in the original study, it is possible that a practice effect elevated their performance. However chi-square tests found no difference in numbers of geometrically correct (C+R) searches across blocks 1-3 with white walls ($\chi^2(2) = 0.19$, $p > 0.9$), and no difference in numbers of correct (C) searches across blocks 1-3 with the blue wall ($\chi^2(2) = 0.13$, $p > 0.9$).

Discussion

The main features of the previous results were replicated. In the all-white condition, subjects searched predominantly using room geometry, despite restricted viewing angle and lack of binocular depth which might make geometric cues less apparent than in a real room. It can be concluded that the virtual room would provide a good basis for manipulations of other factors.

A1.2 Pilot study 2

The purpose of this study was to determine whether physical disorientation (by turning) was necessary to produce a disregard of colour in verbally shadowing adults, or whether merely not knowing one's heading was sufficient. In the previous study, subjects were disoriented virtually, fixating a cross for 30 seconds before seeing a new (random) view of the room. In this study, virtual disorientation was compared with real disorientation, in which subjects spent the 30 second period turning on the spot with eyes closed, as had those in Hermer and Spelke's original environment. If shadowing subjects' previous failures to use the blue wall depended specifically on disorientation by turning, such failures should be seen in shadowing subjects who were turning, but not in those who were only disoriented virtually.

A pilot study with 12 subjects found that although shadowing subjects made more errors than those not shadowing, few of these were "rotational equivalent" (R) errors consistent with a preference for geometry over colour. The length of the virtual room

was therefore extended by 1/3 to enhance that cue, which may have transferred less well than colour to a flat display with a limited field of view.

Method

Subjects

20 undergraduate native English speakers took part in the study. Three did not perform the shadowing task to criterion (see *Analysis*) and were excluded, leaving 17 (7 male) with mean age 21.1 (s.d. 3.1) years.

Apparatus

The virtual "blue wall" environment from pilot study 1 (one blue wall and three white walls), extended by 1/3 to dimensions 225 x 123 x 185 cm, was presented on all trials. The monitor was mounted at head height so that the task could be done standing up. The testing room was dimly lit by a single light projecting a spot onto the centre of the ceiling, providing no directional light cue to subjects turning with eyes closed during the disorientation phase.

The shadowing stimulus, plus low continuous white noise masking any external orienting sound, were played through wireless headphones. In the nonshadowing conditions only the white noise was heard. A microphone recorded verbal performance on the shadowing task. Political and business articles from The Times were chosen. On initial piloting the stimulus was too difficult to shadow. Linda Hermer (personal communication) also judged it to be too fast. The articles were read out more slowly for a second recording, but with agaps greater than 0.5 seconds cut to 0.5 seconds to restrict subjects' opportunities to pause. The final stimulus could be shadowed in real time by most subjects, although not without clear effort.

Design

The experiment had four conditions in a 2x2 (shadowing / not shadowing, turning / not turning) within-subjects design, with four trials in each condition. Subjects were randomly assigned to one of four orders. Either the first two blocks or the last two blocks included shadowing, while either the middle two blocks or the first and last block included turning. Both shadowing blocks therefore always occurred consecutively (since shadowing required a two minute "warm up" period), and no more than one task requirement, shadowing or turning, changed between one block and the next. As in pilot study 1, hiding locations were randomised so that each block included all 4 locations, and no block began with the location on which the last ended.

Walls faced after disorientation were also randomised so that each wall was faced once in every block.

Procedure

Subjects first practiced the disorientation procedure (see below), and were familiarised with the computer task in a landmark rich virtual environment. Before the two shadowing blocks, subjects began the shadowing task on its own, continuing for two minutes or until they could shadow fluently. Without stopping shadowing, they then began the computer task.

In the computer task, subjects began facing a randomly predetermined wall, looked around the virtual room, and saw an object hidden in one corner. After the disorientation phase (see below), the subject's virtual orientation was changed to face the centre of a predetermined wall, and they used the mouse to look around and search a corner, receiving feedback as before.

In non-turning blocks, an on-screen cross was fixated for the 30 second duration of the disorientation phase. In turning blocks, an arrow instructed subjects to step back from the monitor, close their eyes, and turn for 30 seconds. The experimenter tapped subjects to signal changes of direction while walking slowly around, occasionally changing direction, to avoid acting as a landmark. After 30 seconds subjects were stopped from turning, opened their eyes, and walked back to the computer to make their response. On the first (practice) turning trial, subjects were asked to point to the door of the room with their eyes still closed, and their pointing directions were recorded. This measure was used to confirm that the turning procedure was sufficient to induce disorientation.

Analysis

For each condition, rates of correct (C) search, geometrically correct (C+R) search, and colour correct (C+N) search were compared with chance. A repeated-measures ANOVA examined the effects of shadowing and turning on mean proportions of C searches.

Audio recordings of shadowing performance were transferred to a PC and examined on screen so that gaps could be measured. Subjects with a gap longer than 2 seconds during any trial were excluded from the subsequent analysis. This criterion, from Hermer-Vazquez *et al.* (1999), was intended to reject subjects who might have paused for long enough to form a verbal phrase describing the hiding place.

Results

Shadowing performance

Three subjects left gaps longer than 2 seconds, and were excluded from further analysis. For the remaining subjects, the mean pointing error on the practice turning trial was 80.5° (SD 52.1°), not significantly lower than chance (90°) on a one sample t-test ($p > 0.4$). This confirmed that the turning procedure was sufficient to disorient subjects so that their judgments of heading were at chance.

Patterns of search

Figure 34 shows the rate of search at each corner by condition. The rate of correct (C) search in the baseline (not shadowing, not turning) condition (Figure 34, top left) was 92.7%, which closely matches the 91.3% rate for the blue wall condition in pilot study 1. As Figure 34, shows, the rate of C search declined as a function of both the shadowing and the turning manipulations, and was lowest when subjects had to do both (bottom right, 64.7%). Nevertheless, the rate of C search remained far above chance (25%) in every condition.

No condition showed the similar rates of correct (C) and rotationally equivalent (R) search that would suggest the selective use of geometry but not colour. In the shadowing and turning condition (Figure 34, bottom right), where these figures were closest, the rate of R search (10.3%) was still far below the rate of C search (64.7%). Indeed, R searches were not the most common errors in that condition, but N searches (16.2%) were.

The sums of C+R searches were used to evaluate use of geometry, while sums of C+N searches evaluated the use of colour. Rates of C+R search were significantly greater than chance (50%) on binomial tests (for every condition, $p < 0.001$), confirming the use of geometry. Rates of C+N search were likewise greater than chance (50%) for every condition ($p < 0.001$), confirming the use of colour. As well as being far above chance, rates of colour-correct C+N searches were actually greater than or equal to geometry-correct C+R searches in every condition (see Figure 34), since Ns were more frequent than Rs. So not only was there no evidence for a disregard of colour, there was a trend for subjects to favour colour over geometry.

Not shadowing & not turning

C		F
	92.7 1.5	
	2.9 2.9	
N		R

C+R = 95.6
C+N = 95.6

Shadowing & not turning

C		F
	83.8 5.9	
	5.9 4.4	
N		R

C+R = 88.2
C+N = 89.7

Not shadowing & turning

C		F
	88.2 0.0	
	10.3 1.5	
N		R

C+R = 89.7
C+N = 98.5

Shadowing & turning

C		F
	64.7 8.8	
	16.2 10.3	
N		R

C+R = 75.0
C+N = 80.9

Figure 34. *Rates of search (%) on the virtual blue wall task, under verbal shadowing (right), non-shadowing (left), turning (bottom) and not turning (top) conditions.*

Incorrect (R, N, F) searches in this study did not reflect a systematic disregard for the colour any condition. The errors subjects made were therefore not those predicted. Nevertheless, it can be asked how the two experimental manipulations influenced the frequency of these errors. A repeated-measures ANOVA comparing mean rates of correct search found a significant effect of *shadowing* ($F(1,15) = 18.3$, $p < 0.001$), a significant effect of *turning* ($F(1,15) = 4.6$, $p < 0.05$), and an interaction between these factors ($F(1,15) = 8.7$, $p < 0.05$). These patterns are evident in Figure 34. Compared with the baseline condition (top left), the rate of correct search fell by 9% with shadowing alone, and by 5% with turning alone. With both shadowing and turning, it fell by 28%, showing an interaction.

Other observations

Over the course of this study, we saw an interesting phenomenon. After opening their eyes in the dim room, subjects who had been turning on the spot often started walking in the wrong direction, seemed surprised, and stopped to correct their course towards the computer.

Initial steps in the wrong direction did not seem to be the consequence of impaired motor control resulting from the turning procedure, which was not fast enough to induce vertigo. It seemed rather that at least some of the time, disoriented subjects who had just opened their eyes had an erroneous representation of the computer's location, and that this representation dominated over visual information for long enough to initiate a movement in the wrong direction. This observation is discussed below.

Discussion

Each of the two manipulations, verbal shadowing and turning on the spot, significantly diminished participants' rates of finding the hidden object. However Hermer and Spelke's main result, a selective disregard of colour in disoriented verbally shadowing adults, was not replicated. Subjects showed a robust use of colour even when both shadowing and turning. In fact, errors indicating a selective disregard of geometry (N) were more frequent than those indicating a selective disregard of colour (R).

There are three reasons why participants may have continued to use colour in this virtual space, when they could not in Hermer and Spelke's real space: the shadowing task was not difficult enough, geometry was not salient enough to dominate over colour in a virtual world projected on a flat screen, or subjects were not really disoriented with respect to the virtual space.

First, it should be asked whether the shadowing task was difficult enough to reproduce Hermer and Spelke's result. The decrease in turning subjects' performance produced by shadowing, from 88% correct searches to 65%, was not as great as theirs (81% to 43%), but did produce enough errors to show a pattern of disregard of colour, if there was one. In those errors that occurred, there was little evidence for confusion of the C corner with its rotational equivalent R. N-searches, which are inconsistent with geometry, were more common.

A more likely reason for the failure to replicate was the flatness of the virtual space. In this projection, which lacked depth and had a restricted field of view, room geometry may have been less easy to see than wall colour. Even more importantly, although the procedure and duration for disorientation by turning matched Hermer and Spelke's, there was an important difference in participants' state by the time they

searched: as they had to resolve their orientation (within the real room) to find the computer and begin the search task, they were no longer really disoriented. They were still "disoriented" in the virtual space, but no more so than were subjects who had fixated the cross for 30 seconds.

In one respect, then, these results may have revealed something about the role of disorientation in the original studies. Adding together the two characteristics of disorientation – the physical demand to turn on the spot, and the cognitive demand to resolve orientation – did not cause subjects to disregard colour when their disorientation was not linked with the need to resolve orientation in the (virtual) task-space. This is consistent with a specific role for the disoriented state – and not just for the turning manipulation - in producing the result. Spelke's account of this role is that it triggers the "geometric module" for reorientation.

Appendix 2: Experiment 9, matches between WS and control data

Eight ANOVAs compared each of the two WS groups with each of the four control groups. Table 5 lists the p-value for each effect and interaction in each of these.

	room	*body*	*r x b*	*group*	*g x b*	*g x r*	*g x b x r*
WS 16-44 vs. C 3	**0.001**	**0.001**	0.072	0.053	0.605	**0.001**	0.971
WS 16-44 vs. C 4	**0.001**	**0.004**	0.055	0.335	0.669	0.057	0.890
WS 16-44 vs. C 5	**0.001**	**0.003**	0.986	**0.001**	0.941	0.979	0.061
WS 16-44 vs. C 6	**0.001**	**0.002**	0.605	**0.001**	0.865	0.180	0.168
WS 8-15 vs. C 3	**0.001**	**0.001**	0.332	0.213	0.412	**0.001**	**0.023**
WS 8-15 vs. C 4	**0.001**	**0.001**	0.431	0.189	0.137	0.127	**0.028**
WS 8-15 vs. C 5	**0.001**	**0.001**	**0.036**	**0.001**	0.239	0.979	0.549
WS 8-15 vs. C 6	**0.001**	**0.001**	0.083	**0.001**	0.149	0.277	0.295

Table 5. Results from ANOVAs comparing each Williams Syndrome (WS) age group with each control (C) age group. Left to right, the columns list p-values for main effects of body consistency and room consistency, the body x room interaction, main effect of group, and the interactions of group with body, room, and both body and room. Effects significant at the 5% level are bold.

The 16-44 year old WS group, listed first in the table, was easily matched to a control group. On overall performance (main effect effect of *group*) this group was most similar to control children aged four years ($p > 0.3$). In this same comparison none of the interactions with *group* reached significance, showing that the profile across conditions was also well matched to control age four.

The 8 - 15 year old WS group, listed next, matched control age three years best on overall performance ($p > 0.2$ for main effect of *group*). However in this comparison there were two interactions with *group* and the spatial factors, showing that the profile across conditions was not matched. This group could also be matched to control age four years on overall performance (*group* $p > 0.1$), but in this comparison a significant three-way interaction of both spatial factors and *group* likewise shows that the profile

was not matched. Comparisons with five- and six- year old controls had strong effects of *group* ($p < 0.001$) corresponding to a mismatch of overall level.

Appendix 3: Experiment 10, other developmental tests

British Picture Vocabulary (BPVS), short-form

The BPVS (short form) measures vocabulary development using a procedure in which children select the line drawing that matches a single spoken word (Dunn *et al.*, 1982).

Test of Everyday Attention for Children (TEA-Ch)

Children were tested on a subset of the TEA-Ch (Manly, Robertson, Anderson, & Nimmo-Smith, 1999), measuring selective and sustained attention in the visual and auditory domains, and verbal and motor response inhibition. These tasks correspond, broadly, to abilities known to depend on the frontal lobes in the adult and animal literature. The TEA-Ch has been shown to be sensitive to impairments in clinical groups defined behaviourally (*e.g.* ADHD; Heaton, Reader, Preston *et al.*, 2001) and neurologically (*e.g.* traumatic brain injury; Anderson, Fenwick, Manly, & Robertson, 1998).

Motion and form coherence thresholds

These are tests of perceptual discrimination for coherent visual motion and visual form hidden in incoherent noise. They tap low-level processing associated with the dorsal visual stream (motion) projecting to the parietal lobe, and the ventral visual stream (form) projecting to the temporal lobe. These tests, illustrated in Figure 35, were developed in the Visual Development Unit. High thresholds (*i.e.*, reduced sensitivity) for motion detection in particular are found in groups with Williams Syndrome (Atkinson *et al.*, 1997), hemiplegia (Gunn, Cory, Atkinson *et al.*, 2002) and Fragile X (Kogan, Bertone, Cornish *et al.*, 2004), in which they suggest impaired dorsal-stream function.

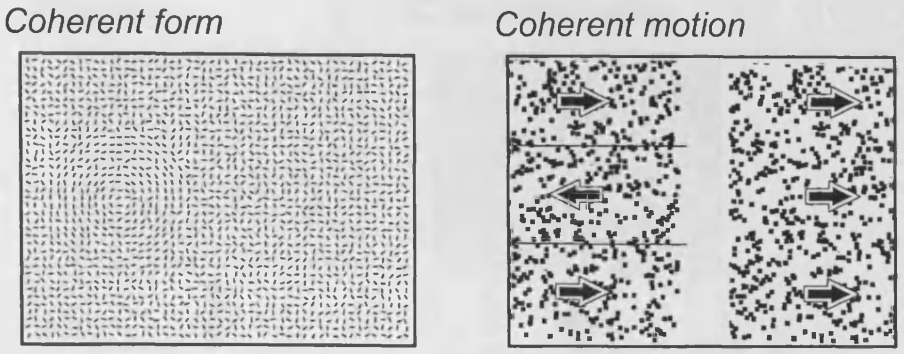


Figure 35. *Diagrams of stimuli for detection of coherent form (left) and motion (right). In the form stimulus, the task is to point to the side of the screen with the figure made up of coherently oriented lines ("the ball in the grass"). In the motion stimulus, the task is to point to the side of the screen with a central section of dots moving coherently in the opposite direction to the top and bottom sections ("the road in the snowstorm"). Detection thresholds are estimated by increasing and decreasing the proportion of noise (incoherently oriented lines or incoherently moving dots) according to a staircase procedure.*

Pointing and counter-pointing

This test of rapid visually guided action was also developed in the Visual Development Unit. Targets appear on a screen, to the left or right of a central fixation point. In the "pointing" condition the task is to touch the target as quickly as possible. In the "counter-pointing" condition, the task is to touch the opposite side of the screen (see **Figure 36**Figure 36). The counter-pointing condition therefore includes a test for inhibiting a prepotent motor response, a "frontal" ability.

Block construction

In this task participants use blocks to copy a construction made by the experimenter (Atkinson, Anker, Rae *et al.*, 2002). This combines the perceptual demand to decompose the construction into its block elements with visual planning and motor demands. Children were tested on three constructions, "arch", "enclosure" and "cross". The measure was total time taken to construct all three.

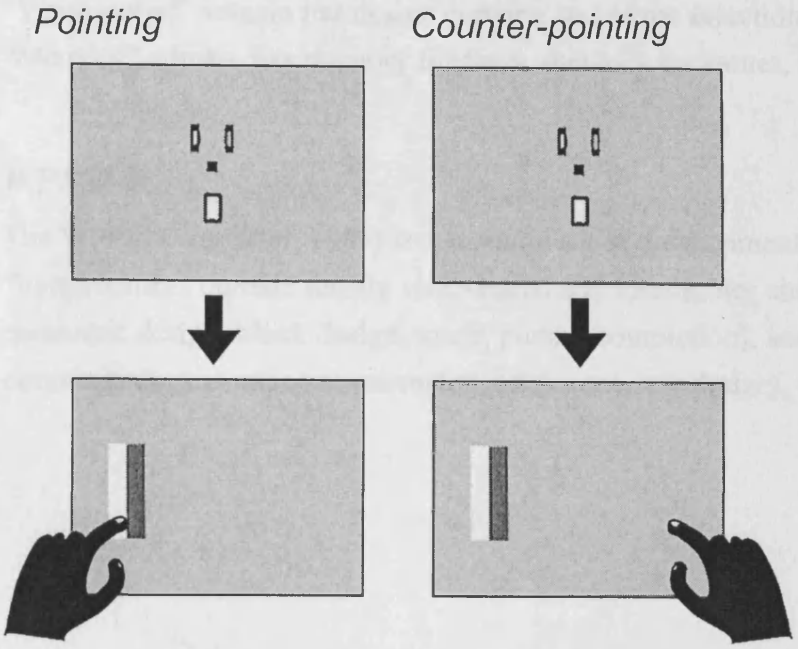


Figure 36. *Stimuli for pointing (left) and counter-pointing (right) trials. A central fixation stimulus is followed by a target (vertical bar). On pointing trials the task is to touch the bar as quickly as possible. On counter-pointing trials the task is to touch the opposite side of the screen as quickly as possible.*

Movement Assessment Battery for Children (Movement ABC)

This is a standard battery of developmental tests of motor and visuomotor ability (Henderson & Sugden, 1992). It includes tests of gross motor skill (balance) - walking on tiptoe, balancing on one leg, jumping over a cord; tests of fine motor skill (hand-eye coordination) – threading beads, posting coins through a slot, using a pen to follow a 'bicycle trail' on paper while staying within the 'trail'; and tests of ball skills - catching a bean bag (rapid visuomotor coordination) and rolling a ball so that it passes between two goalposts (a test of visuomotor planning).

NEPSY

The NEPSY (Korkman, Kirk, & Kemp, 1998) is a new, extensive battery of developmental tests. The "Attention / Executive" domain comprises a version of the Tower of London task (planning / executive), and tests of auditory and visual attention. The "Language" domain has phonological processing, speed naming, and comprehension of instructions. The "Sensorimotor" domain has finger tapping, imitating the experimenter's hand position, and visuomotor precision. The

"Visuospatial" domain has design copying and arrow direction judgment. Finally, the "Memory" domain has memory for faces, memory for names, and narrative memory.

WPPSI-R

The WPPSI (Wechsler, 1989) is a standard set of developmental tests, with five in a "Performance" domain testing visuospatial and visuomotor ability (object assembly, geometric design, block design, maze, picture completion), and five in a "Verbal" domain (information, comprehension, arithmetic, vocabulary, similarity).

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